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Science Policy Study—Hearings Volume 10
THE IMPACT OF THE INFORMATION AGE ON SCIENCE

ORIGINAL

HEARINGS

BEFORE THE

TASK FORCE ON SCIENCE POLICY

OF THE

COMMITTEE ON
SCIENCE AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

NINETY-NINTH CONGRESS

FIRST SESSION

SEPTEMBER 10, 11, 12, 1985

[No. 103]

Printed for the use of the
Committee on Science and Technology

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CONTENTS

WITNESSES

Page

- September 10, 1985:
  - John Diebold, chairman, Diebold Group, Inc., New York, NY 2
    - Discussion 8

PANEL

  - Dr. Robert Langridge, director, Computer Graphics Laboratory, University of California, San Francisco, CA 16
    - Philip Elmer-DeWitt, "Artistry on Glowing Screen," Time, August 5, 1985, pp. 68-69 21
    - Ron Dagani, "Supercomputers Helping Scientists Crack Massive Problems Faster," Chemical & Engineering News, August 12, 1985, pp. 7-13 23
    - Paul A. Bush, Nagarajan Pattabiraman, Conrad Huang, Thomas E. Ferrin, and Robert Langridge, "Van de Waals Surfaces in Molecular Modeling: Implementation With Real-Time Computer Graphics," Science, December 23, 1983, Vol. 222, No. 4630, pp. 1325-1327 30
  - Dr. Paul A. Vanden Bout, director, National Radio Astronomy Observatory, Charlottesville, VA 34
    - Prepared statement 47
  - Dr. George J. Armelagos, professor of anthropology, University of Massachusetts, Amherst, MA 75
  - Panel discussion 84
- September 11, 1985:
  - Dr. David Pensak, research supervisor, computational chemistry, E.I. duPont de Nemours, Inc., Wilmington, DE 90
    - Prepared statement 96
      - David A. Pensak, "Modeling System Cuts Wasteful Steps From Complex R&D," Industrial R&D, January 1983 107
  - Dr. J. Freeman Gilbert, professor of geology, University of California at San Diego, La Jolla, CA 113
    - Prepared statement 125
  - Dr. John Hubbard, professor of mathematics, Cornell University, Ithaca, NY 138
    - Prepared statement 144
  - Discussion 152
- September 12, 1985:
  - Dr. Patricia Battin, vice president and university librarian, Columbia University, New York, NY 164
    - Prepared statement 169
  - Dr. Allen Newell, U.A. and Helen Whitaker, university professor of computer science, Carnegie-Mellon University, Pittsburgh, PA 179
    - Prepared statement 184
  - Dr. John Seely Brown, principal scientist and director of Intelligent Systems Laboratories, Xerox Palo Alto Research, Palo Alto, CA 193
    - Prepared statement 198
  - Discussion 217

THE IMPACT OF THE INFORMATION AGE ON SCIENCE

TUESDAY, SEPTEMBER 10, 1985

House of Representatives,
Committee on Science and Technology,
Task Force on Science Policy,
Washington, DC.

The task force met, pursuant to call, at 10 a.m., in room 2318, Rayburn House Office Building, Hon. George E. Brown, Jr. (acting chairman of the task force) presiding.

Mr. George Brown. Let's begin this morning. This is a meeting of the Task Force on Science Policy, which for the benefit of any of you who have not been participating, is a roughly 2-year effort to review the situation, the condition, of science and technology in a comprehensive way, to determine if there are major changes in this policy which ought to be considered by the Congress.

In some ways, it is analogous to the original efforts which went into the preparation of the report called "The Endless Frontier," which is looked upon as a landmark in terms of establishing a new structure of science policy for this Nation.

I don't want to be too grandiose about our efforts today, but it is one of those once-in-a-generation efforts aimed at reviewing where we are, and where we have been, and where we ought to be going.

The series of three meetings, of which this is the first, is aimed at focusing specifically upon the question of the impact of the information age on science.

Now, this title will mean different things to different people. The very mention of the term "information age" is somewhat ambiguous, but I think it is to the credit of the Science Committee that we have recognized for a number of years that the new technologies and information were revolutionizing the nature of our society, and we have sought to maintain some grasp over these changes as they occurred, some conceptual grasp anyway, and these three hearings are intended to strengthen our capability in that regard.

We are very fortunate in having a very distinguished group of witnesses this morning, led off by Mr. John Diebold, chairman of the Diebold Group of New York, which I don't know what they have been into recently, but at one point, they were—I considered them to be one of the top management consulting fields in the country, and I presume you still do some of that?

Mr. Diebold. Yes, sir.

Mr. George Brown. So, we are very—we are very pleased to have you here, and I have a copy of your latest book right in front of me, and I am sure we will read it with great interest when we get the opportunity, and you can digest it for us this morning, plus adding anything else that you like.

Do you have anything you would like to say?

Mr. **Lujan**. No, Mr. Chairman.

Mr. **George Brown**. All right, you may proceed.

STATEMENT OF JOHN DIEBOLD, CHAIRMAN, THE DIEBOLD GROUP, INC., NEW YORK, NY

Mr. **Diebold**. Mr. Chairman, members of the committee, it is a great honor to be the lead witness on the first day of these hearings. I would like to compliment the committee on having these hearings on the impact of the information age on science.

Information technology is itself the product of science, but it is also having an ever-greater impact on the way in which science is practiced and on the future of science, and it seems to me to be a child of science that is indeed changing materially the way in which we go about science.

Following me today on this first morning of testimony are a pharmaceutical chemist, astronomer and anthropologist, I think that is reflective of the way in which virtually all fields are being changed by information technology, and I think that it is a very good way of demonstrating just how extensive the impact of information technology is on the way we go about science.

Just as information technology is changing both the way we work, it is also changing what kind of work we do. A young astronomer today, for example, will choose a completely different career, a completely different set of problems to focus on in their lives as a result of information technology, and it is not simply the calculating speed.

It took Kepler 4 years in the 17th century to calculate the orbit of Mars, something which we have been doing in minutes, and now in parts of seconds. Partly it is that, but partly it has changed the complete infrastructure of the way one goes about practicing most professions and very much true of science.

So, it is changing the science in the most fundamental ways. I think it is useful in setting the stage for these hearings if you step back a little, and on the question of what is information technology and where it came from and where it is going, because it is really the combination of two things.

Some theoretical work that was done in the 1930's and 1940's, by people like John Vonor at Princeton, Allen Turing at Cambridge, T. Court Shannon at Bell Labs, a small group of people who are interested in the theoretical issue of the nature of information, the nature of communications. It was this work, linked with the emergence of electronics, and the ability to build machine systems, to handle and communicate information to do with it what we want, and the combination of these two strands, the electronics being supplemented by optics, soon to an increasing extent by developments in the fields of neurobiology. But the combination of the technological capabilities with the theoretical insights into the nature of information are really where all those have come from, and once talk is about a very short-time period that was the theoretical work in the thirties and forties, and the emergence of computers in the form we think about them in the forties. but you didn't begin to have any real proliferation until the fifties.

And from then, it has increased, and the form has changed, the speeds and the costs have decreased, and the faster and the cheaper it is to do the calculations, the easier it is for the human being to use the machine, because you can make the machine more and more complex at lower and lower cost, and it allows for more complexity within the machine, but it makes it available to the ordinary human, more and more readily to make use of the machine where we are into a period now where the ability to recognize voice and to respond in human voice, the graphic abilities are continuing to improve. The man-machine interface is changing materially that is proliferating the use of technology, and it is a very important part of changing the whole infrastructure of the practice of a profession and of any professional affecting science materially.

I think that when you focus on the fact that information and its communication are really the major determinants of human organization, it is not surprising that this technology is changing the whole fabric of the society, and we are just beginning to see the first examples of that, but it is going to be more and more true as we move along.

So that you have a very fundamental change going on in regard to information technology and in its application through the mechanisms of technology. In many ways, the technology is outpacing policy, and I think that will increasingly be true, and it has put a particular burden on the question of science policy.

I have six observations on which I would like to focus. The first is the longest, but they are each very brief comments.

First is that in no field are the mechanisms of application of science to society more important than in information technology. The intricate interrelationship of institutional relationships which allows us to take scientific insights, to apply them for human betterment, for jobs, for a better society in all respects. The interplay in this area in the case of information technology is extremely important, and I think that it is worth focusing on, and that is my lead comment in this regard.

I think that most people would agree on the importance of the highest quality basic pure science. My own rule would be that any society ought to fund to the fullest first-class scientists to the extent the society is fortunate enough to have them. That isn't enough, and if one is focusing on science policy, the question is how does society benefit from the insights of science? I think it is that interplay which should be focused on very much, and I don't think you can focus on science policy effectively and certainly not in the case of information technology, without a lot of attention to the institutional relationships involved in getting this applied, and getting it used.

America has been extremely strong, uniquely strong in this regard. If you contrast it in the information technology field with, for example, England, where some of the very best original theoretical work was done, and some very best science was done on computers, yet, with the continuing inability to bring those to market, a continuing inability to have the society really benefit from what was first-class science that was going on.

I think America has been uniquely strong, and it is not simply in a contrast with England, it is true with regard to most other countries. It is very fashionable today to focus on the advantages the Japanese have because of unique cultural characteristics of their society. We have some unique cultural characteristics as well, and some of those have been working very much to our benefit in this particular regard.

Our ability to innovate is something that has been commented upon by observers for as long as we have been a country. Our Yankee ingenuity. Our mobility from job to job, the ability of people to move—the interplay between business and the university, which has been increasingly strong.

I think one of the unique characteristics has been the ability to fail. In most other societies, you can't fail. You therefore don't take risks as readily. There is a very strong focus on, at the moment, in Europe on why can't any particular political jurisdiction you are focusing they want to be the Silicon Valley of whatever area, Wales, the Rhine, the Ruhr, wherever you, whatever field you are in, they want to be, they want to make their area the Silicon Valley. They focus on things such as venture capital. The problem in Europe as it is in Japan is that if you gave venture capital to a young person, they have a severe set of cultural problems in taking risks with it. If they succeeded in many countries, their families still look down on them because they didn't go into a large organization or they didn't go into the government. If they fail, in various countries, in Germany for example, 28 years of personal liability on bankruptcy. That is what the lawyers call a chilling factor. You don't get risks taken. We have a lot of unique characteristics in this country that have been strong, yet I think there are some negative factors, and the whole fabric of this ought to be focused on in trying to determine what one can do in terms of being sure we do stay ahead in information technology.

A single example of one of the negatives, I think, is that we have still a very substantial adversarial relationship between business and Government. This is very difficult, and other countries, Japan being a perfect example of the reverse of that. But we have an adversarial relationship which is not helpful in this transition problem, in the transition mechanism. I don't think it needs to be that way. I would like to take a single example of where some really creative political thinking, creative political invention, made a difference, that is in the greatest success story of American technology.

The greatest success story of our technology is agriculture, and the changes that took place in the application of science through transition of the technology into the entrepreneur are things that started with the bill Abraham Lincoln signed, creation of land grant colleges, successfully the creation of county agents who become very effective technology transfer mechanisms, onto the entrepreneur, the farmer.

I think that if we focus today on the heavy subsidies in agriculture, the subsidies really didn't start getting very heavy until the 1920's and 1930's. The material change in productivity came earlier than that, and I think it was a marvelous example of a nonadversarial relationship and of a very constructive set of political inventions that took place. And I think that my first point is really that that whole set of institutional relationships ought to be a serious focus.

My second point, I think very briefly, is the importance of lead time in innovation and the increasing importance of lead time. The main thing that we have in terms of United States international competitiveness is the ability to effectively innovate and to get to market the innovation, but the lead time is absolutely crucial and anything that cuts down on that lead time, whether it is the Japanese, for example, I think one of the serious issues in regard to the international competition is the problem that in the new industries, Japan has consistently followed a policy of making it difficult if not impossible for foreigners to come into Japan in new fields until the Japanese companies have gotten up to speed on those. It eliminates the advantages of our lead time, and I think that far more than any of the indirect subsidies that occur in Japan might very well be a real focus of our concern in this area. I am not a perfectionist, but I think this is an area where the lead time is absolutely crucial. Similarly, internal things which hammer the lead time and cause us problems also ought to be focused on in terms of domestic policy, because that is lead time which is getting ever shorter which is the most crucial element of U.S. technological competitiveness.

The third point is with regard to internationalization of science policy, and again, I would like to suggest that some of the aspects that also ought to be the subject of your attention is the question of the way in which we are competing internationally and the extent to which American institutions are or are not able to take part in some of the international developments, and these occur over a wide range of things.

The blocks that the PTTs in many countries have established are both an example of technology outpacing policy in the sense that their policies have been established long before the present technological capabilities of data flow were evident, but the blockages that are established there are very important in terms of our ability to compete in those countries. The question of the ability of a subsidiary of an American multinational in another country, if it is a French subsidiary, employing only French citizens, doing sizable business in France, it is allowed to take part in the EEC's joint research projects, and benefit from those. These are very real questions of the kind that in terms of going after making sure that we are able to be competitive internationally, I think are far more important in the emerging industry than the subsidy questions that are involved.

There have been some improvements that appear to take place, recently the Japanese have opened in the consultative process internally, they have opened two American companies, to take part in this, in terms of what kinds of technology would be acceptable for use. It remains to be seen how real that is. But there are a lot of areas of that kind where we need to, as I think from the standpoint of U.S. policy being focused on these very much.

As we get into a postmultinational, as we get into the world in which you have a change of the multinational that we have seen in the last 25 years, into a postmultinational forum, you are going to have a much more severe set of issues of this kind. Knowing what it is we ought to be bargaining, seems to be to me one of the most useful things the Congress might do in terms of exploration and review.

I am cutting—I am trying to stay within your time constraints, these are all things that each should have a lot more said about them.

My fourth observation is with regard to the application of science and especially information technology to the public sector, the public service delivery. Public service delivery is characterized by being labor-intensive, by using relatively little science or technology, and, I think, as part of the issue of what impact information technology will have on our society, it seems to me that one of the important things is to focus a little bit on why it is so, why is the public sector such a poor user of the fruits of science? Why do we in the case of education, for example, deny people the benefits of a technology which we are applying very creatively in a lot of things which are much less, I think, personal subject observations, but much less important in a society, some of the consumer products, but in vital things such as public education, we are not using the fruits of this science.

We are not doing the work on learning process. I am not talking here about getting people to use computers, I am talking about understanding the learning process enough so that we can try to use information technology in all its forms to make it possible for a poor child to get as good an education as a rich child.

Today you can't. And today, a child as a child, has to go at a certain speed in a classroom, and you may get left behind. I got left behind in language classes all through school, I wasn't able to go into my field of first choice, because I went to Swarthmore, you had to have Latin or Greek plus a modern language. I couldn't do languages. If I had been in the classroom in which you used creatively information technology, I would have had that language capability. I chose a different career, had to, I am not objecting, but totally different career than I would have.

But I think that the question of why we don't do a better job ought to be focused on. It seems to me to be two possibilities. One is to put into the market, so that there is an incentive for R&D, and I think to me the main argument for privatization of public service is the fact that you will get an outpouring of research money. You would, if you could get a belief that there would be political tolerance of profit in these sector for long enough period of time to cover it, you would have completely different kinds of school systems. You would have completely different kinds of systems for running cities than we do today. You would use science and technology. If we are not going to do that, then it seems to me some public demonstration projects, for example, and information technology in education, it has got to come one way or another, and it seems to me a useful focus would be on this.

My fifth observation is with regard to information technology as a productive mechanism in the conduct of science. I think it is too easy to view it as an instrument and as—actually it is going to be very hard in a few years to tell an instrument from a computer, because they are simply merging and they are going to be increasingly merged. You are not going to be able to say this is a computer and this is an instrument; most instruments are going to look to look like computers. It is simply changing instrumentation, and I think the committee should be complimented on the hearings you have held on instrumentation and infrastructure, and that is a very right place to be focusing on this, complimented.

What I am trying to focus on is the fact that it changes materially the atmosphere, the way in which professional work is done, and it does it the way, if I can use historical analogy, we had a big change in productivity in this country in the last two decades of the 19th century, and first three or four decades of this century, in the manufacturing sector. That came through the application of very heavy investment in machinery, but it also came in a big shift of labor force from blue collar to white collar. To some people, that is viewed as overhead, to other people, if you take the historian Fred Chandler at Harvard in his very good study on this whole process, you realize that the reason the productivity went up as much as it did in direct manufacturing was because, in addition to the machinery you provided the infrastructure, you provided the planning, a lot of these growth in jobs in the white collar side were doing making the blue collar people productivity by doing the planning by doing much more intensive research and rationalization of the whole production process.

Same thing is happening in science. You make the scientist far more productive as a result of the electronic infrastructure that is being provided. And that moves into my last point, which is the role of networks, information networks which I think are absolutely crucial in terms of science. They perhaps raise some interesting problems in how you go about the funding of science, because in today's world, the ability to interconnect systems all over the world, the ability for a scientist to be able to not only draw on a very large number of data bases, but also to be able to communicate with other people doing the work and to be able to change the information, this is vital part of, today, any profession—of none more so than science—and the network aspect is a very, very important part of this.

It is changing the role of libraries. I am a member of the American Library Association Commission on Freedom and Equality of Access to Information, and I have been very struck in the hearings we have had on the question of the extent to which the role of libraries are changing in this entire area.

Again, in terms of science, the ability to have an interplay with many people and many different series of data bases, is crucial. There are other points I might have dwelled on. One I particularly feel strongly about in anything that you do is continuity.

The problem of continuity without year-to-year changes of dramatic amounts. I think that as a trustee of the Carnegie Institution of Washington, one of the things that has impressed me most about Mr. Carnegie has been the fact he focused on the idea you found a small number of exceptional people and simply backed them for

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their productive life, and out of that came a number of capable people and a great deal of insight.

I think continuity in any of these things is extremely important. Continuity of infrastructure funding I think is very important. I think the way in which you view the computer is absolutely vital. It is not something which can be viewed as being pertinent onto a particular project. It is something that is essential to the way a person ought, or a scientist ought to live, and does his work, and this is, I think a very key element. Studying the international models in this area, would seem to me to be increasingly important. I am sorry if I went longer than I should have.

DISCUSSION

Mr. **George Brown**. Thank you very much, Mr. Diebold.

Mr. Lujan.

Mr. **Lujan**. Thank you, Mr. Chairman.

Just one question because all of the points that you raise are very interesting. I am wondering how we attack all of these different points that you raise as to whether or not you think it would be a good idea to have some central Government organization to direct the research in information technology.

What I mean by that is that DOE, for example, does a lot of calculation work because of the work that they are involved in. Then we have the National Bureau of Standards doing work on some of the equipment in terms of security of information, those sorts of things, and the Department of Agriculture, NOAA, dissemination of information. Is it a good thing to proceed with different organizations within Government doing different things or should there be some central organization to make direction in policy?

You mentioned the question of the Japanese. We innovate, and they take it from there and put it into practical use, and all of your other points we could——

Mr. **Diebold**. It is a good question. I think the main thing that is probably needed is some coherence in policies. I mean, I think that the great strengths in this field have come from the divergence of work and the plurality of organizations doing the work, but I do think that in this problem I was trying to focus on of the transition from pure science to its benefits for the society, one of the real problems, people have talked a lot about industrial policy.

Well, it has become a big political issue. But, gentlemen, we have an industrial policy. The problem is we have got all kinds of interplay of incentive and disincentive systems between public and private sector. The problem is that it often works at cross purposes, and it is not a coherent policy.

I have in my book a series of examples of—I cite just one. You have got an FDA ruling, for example, that until a drug is accepted for use within this country, it can't be shipped in interstate commerce. Well, often drugs are accepted in other countries 4, 5, 6 years ahead. Well, American companies that have innovated those drugs are not allowed to manufacture in this country. They have to ship the jobs overseas during that time period because of that rule. You could still keep it from being sold to American consumers until it is approved by FDA, but why ship the jobs overseas? That is what we have been doing.

The IRS has a ruling on expenditures that are allowed for education. If I am a steelworker, and I see the writing on the wall, and I try to take a course in learning how to make machinery to make chips, I can't deduct it, but I can deduct learning more about steel. I can deduct the expense for a deadend job; I cannot deduct the expense for a bright future job, I would think counter to everybody's assumption of what is good public policy.

My estimate is there are about 2,000 such rulings which are counterproductive. It is an incoherent industrial policy, and whether one argues for or against, I mean industrial policy means lots of things to lots of people, but I think the problem of a review to see these things pulling together and of many working at cross purposes would be my focus in answering that question.

Mr. LUJAN. But that is very difficult. Even in your recommendations you talk about networking and interconnections and those sorts of things. When you do that, that makes the information available to those world competitors of ours.

Mr. DIEBOLD. Sure, sure.

Mr. LUJAN. It is very difficult to establish these policies.

Mr. DIEBOLD. Sure. I think many of these problems are far from easy. I mean the whole question is how far you want to go from a national security standpoint. I mean certain things should be curtailed and the problem is what the balance must be. But I think a continuing review of those things is desirable because it changes so fast. Something that isn't a significant issue at one point, a year or two later may be absolutely crucial.

Mr. LUJAN. Thank you, Mr. Chairman.

Mr. GEORGE BROWN. Mr. Lundine has some questions about industrial policy he would like to ask you.

Mr. LUNDINE. I was going to say that it was about the invasion process. You have certainly been very thought provoking. Let me ask you just a few specifics that intrigue me. You talked about the lead time phenomena and Japan. What would you advise us to do about that?

I mean, it is very true, fiber optics and supercomputers would be two good examples where they absolutely have a policy that they are not going to buy any, they don't care where they come from, until they have a competitive Japanese industry. What would you advise us to do about that?

Mr. DIEBOLD. A very much more knowledgeable person than myself, and a friend of mine, Henry Resovski of Harvard, had a piece in the New York Times last Friday in which he was making the point that how indeed do you bring pressure to bear on the Japanese. He suggested that you take video tape recorders, and you do what the French do, you clear them through Kokomo, IN, 3 days a week.

The point I was trying to make is I think we ought to try to learn what is really in our interest, which points, and then you want to exert the maximum pressure in whatever means you can on that. I think this kind of thing is more important than the subsidies. A lot of the focus of the debates has been on the subsidies, and there are all kinds of indirect subsidies and we do, too. We have all sorts of educational and other subsidies. But this lead time problem is horrendous.

Mr. LUNDINE. I agree.

Mr. DIEBOLD. Sometimes it happens not really—I mean, one of the problems, you can be very paranoid in this area because sometimes—for example, the Germans have, and several of the European countries have, in different versions, privacy laws which prevent data from being transmitted. The motive on those laws was genuinely privacy. It looks to us like transported data blockage. Sometimes it depends upon where you sit, but sometimes it really and truly is intended to be a transported data block and is in the guise of a privacy law so it is a very complex set of questions as to how did some of these things come about, but I think there is no question about the effectiveness of the Japanese in industry after industry in following this policy.

Mr. LUNDINE. What do you mean by a postmultinational period?

Mr. DIEBOLD. Well, a postmultinational corporation.

Mr. LUNDINE. Corporation, yes.

Mr. DIEBOLD. I think that you are getting again reality outrunning policy. The multinational corporation came into existence very much in the postwar period, and I don't think Congress discovered it until quite late in the day when in the late sixties, early seventies suddenly Congress discovered the multinational and started to talk about regulation of multinationals. Up to that point it was the one successful international institution going. The same thing is happening now, I think. What is happening is you are getting into a world in which the role of the multinational is changing materially. Look at the nature of the deals that are recounted in each day's papers. You are getting all kinds of really very innovative interplay between American companies and foreign governments and foreign companies which are themselves arms of governments to one degree or to another.

I think what happens is we come more and more to a trading company type of structure. I think we come into a structure where we have much more of a role of innovation, of finance, of marketing and a very different kind of set of relationships than true 10 years ago. It is changing. It has had very little focus on it, but the reality is running far ahead of anybody's focus.

That happened with multinationals. I mean, multinationals really was not the focus of press, was not the focus of the Congress. It was not the focus of the U.N. until very late in the day after the American multinationals had been very successful. Now we enter the period of the Japanese and the Dutch and the other European and other multinationals, but I think that is changing as we look at it, and it is coming into a very different kind of an institution than we think of as multinational at the moment.

Mr. LUNDINE. Can you give me an example of how you would privatize public service, particularly in education?

Mr. DIEBOLD. Well, let me as a prelude to this say really the reason I am so attracted to the question of using markets on public service delivery came from the fact of looking at the question of the application of technology and the fact that if you came from another planet, you spent a half hour walking around the streets of any city in the northern hemisphere, you would be struck by two

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things. You would find shop windows with a plethora of consumer products, personal portable computers, sewing machines driven by chips, portable color television sets, all at quite low cost.

The other thing you would be struck by is the fact that virtually none of the public services use technology except in a peripheral way. They are devoid of it. All the really important things in life, how we run our cities, how we educate our children, these things are run in a labor-intensive manner, poor quality, high cost, increasing cost meaning the quality will continue to decrease, the service range and quality of the service will continue to decrease in these important things.

You would go back to your space ship, and you would write the report, and you would say it is a society of a paradox. They have marvelous science, marvelous technology, great ability to bring these things to the populus, yet they don't do it in all the things that are really important.

Mr. LUNDINE. Right, but what are you going to do?

Mr. DIEBOLD. The reason I got interested in it was that. I think I set up a foundation about 15 years ago initially because of the problem of what the human impact of technological change would be and very shortly felt we weren't doing enough to use it in this area.

We found several hundred examples of privatization working in totally divergent fields. In Denmark 70 percent of the fire departments are run for profit, the child day-care centers to maintenance in streets to—there are examples primarily on the local government level, much, much less so on a Federal Government level all over the place. They are mostly isolated. The ones that are least interesting are where you contract out because you don't really—you get, I mean Scottsdale, AZ, you have a very good for-profit fire department with a very high quality of fire protection at low cost as a result of invasion in light equipment, light trucks, better deployment of vehicles, better deployment of personnel, tighter operation than you do in a comparable town by all independent analyses of it.

That is less important, less interesting, I think, than if you could create a market to compete in these so that you had—so you could aggregate the market, so you could aggregate the demand, so you were able to look at a function internationally or at least nationally so you weren't focusing on one area then the application of science, I think, would begin to be amortized over—would allow you to begin to put the same kind of R&D money as a private player into this as you do to produce a better color television set.

It is very difficult to do. I think at one end of the spectrum is the question of how our streets clean, and you have hundreds of measures of productivity, most of them input and process. How many vehicles, how many tons, how many men, how many hours. You don't have the measures to street clean. At the other end of the spectrum is the child education. We are not even doing the research to know how to answer that question, but it seems to me most things are someplace along that spectrum, and we ought not to escape us to do, to learn how to do that. If the public sector would do more to focus on what we want to achieve and then make it profitable to achieve those things and get competition, you can have the public as a player and you can have private.

The best street and snow removal examples in the country are ones where you have a combination of a city offering those functions and of private players offering the functions, and they mostly seem to gravitate to mixes of about 20 percent city and about 80 percent diverse other players in doing that.

The real problem is to get a market there so that you can get the investment in the R&D. The reason it does not happen there is that the political outcry once you make a profit at doing these things is such that any player starts to be worried is it going to be taken away.

So how much can you afford to put into research, unless you have a political toleration of profit in these functions? I think one way or another we ought to be able to get technology into public service delivery. I think you can either go that route, which is a very tough one politically, or you go the route of really trying to do some major demonstration projects, let private contractors compete in them. This is not like cancer programs. This is like the Moon program. These things are all possible. They are engineered—the scientific solutions are there as they are not in cancer, but it is a problem of how you deploy the engineering. But we are not deploying that engineering in something as fundamental as education.

Mr. Lundine. Mr. Chairman, thank you for your tolerance and time. I just want to intrude on it for one more minute.

I am not sure what it has to do with science policy, but the wisest thing ever told to me when I was a mayor was that you better be very careful how you define productivity because you are liable to achieve it.

Mr. George Brown. Mr. Ritter.

Mr. Ritter. Well, I think Mr. Diebold must recognize that problem, too. You mentioned this lead time phenomenon and what the Japanese do, and then you also mentioned that we could do some things domestically to shorten our lead time. We are in a race with the Japanese as well.

Even if it is not crossing the borders, they are trying to race to get a product commercialized, and we are trying to race to get a product commercialized. From my readings, I understand that lately they are able to commercialize faster. They are just across a range of products. What is it that we might wish to do to shorten the time between the research and development, demonstration activities and the market place.

Mr. Diebold. Domestically you are talking about?

Mr. Ritter. Yes.

Mr. Diebold. Well, it varies a lot by industry. I mean if I go back to my FDA example, I think there is a whole lot that could be done in terms of the ability in the approvals of pharmaceuticals, for example, in the development of them where the lead times are very great in this country. The method of doing it varies from Switzerland to France, to Germany, to England, are very different methods, but tend to be very much shorter and with, you know, a lot of the problem there is the problem of the tolerance of risk, the question as to how much everybody wants to risk society.

Mr. **Ritter**. Exactly. We have known about this problem for years, and everybody is aware and certainly this committee is aware of the far shorter commercialization times of drugs and chemicals and in some areas it is getting worse and in some areas it is narrowing.

Mr. **Diebold**. Well, it is getting worse in most of these areas, because other people are getting more sophisticated and faster at bringing out the products. I mean, what had been really a very long lead time has become really quite short and the learning curve, the problem of doing it is a very important part of it.

The question is actually having the manufacturing experience in the new technologies. Your costs and your ability to produce change dramatically over a relatively short time, and basically that is what Japanese drive for, is to make sure they are protected during that period so that they are able to get their costs down, down that learning curve during a relatively short lead time period, but they go at it very fast.

Mr. **Ritter**. How do we deal with this lesser risk tolerance that, say, our society may have vis-a-vis Japan or Europe?

Mr. **Diebold**. With a lesser?

Mr. **Ritter**. Risk tolerance.

I mean, because that is really what it boils down to when you talk about 5 years there versus 10 years here.

Mr. **Diebold**. Well, you have got, you know, the problem is partly one of, I don't want to say inherent in democracy, but it is. It is partly a problem that you want to be sure—you can be shot down very fast if a mistake emerges, and there is very little incentive to the individuals doing the regulating to speed it up.

The problem of—Lord Rothchild gave a very brilliant paper on this which was printed in this country a few years ago on the contrast of the—as soon as something becomes the political focus, everybody wants a risk-free situation in which you don't have any failures, and achieving those, you end up endangering far more lives than you would if people took the drug; the problem of determining how many people would die from a malady might have been prevented, in contrast to what might have gone wrong in a drug. That is not my field. I think the man that is following me comes from that world. And I don't want to live in a society where anything can be put on the market in the way of a drug either. But I think there is a problem of the speed of approval in that area.

Mr. **Ritter**. Getting away from that very controversial area, what about in other product areas in terms of lead time in commerical R&D that is, maybe, on the shelf somewhere, we are working on, and we find all of a sudden the Japanese have done it or it has been done? Where are some of the shortenings that can come about?

Mr. **Diebold**. Well——

Mr. **Ritter**. From your perspective.

Mr. **Diebold**. Where they are able to be put on the market directly without any approval procedure, I don't see problems of that kind. I think you encounter those when you have regulatory situations is where and we have been moving, I think, in the right way in the sense of less started during the Carter administration to move toward deregulation.

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I think those were healthy things generally. But the regulation has been one of the things that has slowed down in certain industries, slowed this down.

Mr. RITTER. One last point. You mentioned that we do have a lot of industrial policies and the goal would be greater coherence within and amongst those policies. And there have been many recommendations in this debate. Some here in Congress. How would you recommend that we try to rationalize this enormous area of different industrial policies?

Some have said we need a committee of industry, academic, labor, 16, 18 people. They would have a congressional mandate, and they would divide up all these problems. How would you do it?

Mr. DIEBOLD. Well, to begin with, I would make sure that the agency doing it couldn't become a trough, that it couldn't fund anything. I think one of the major points at which industrial policy sticks in the craw of a lot of people is with regard to the question of whether it is going to be a question of subsidizing and simply a big public trough that opens up.

I don't think it has to be that way, but it does seem to me there could be interdepartmental committees aimed at the problems of saying what are the objectives that we have.

You have got rule 861 of the IRS says that R&D expenditures can be deducted only in the extent of the sale domestically of the products. Well, if you have 50 percent of your product being sold overseas and 50 percent here, you are left to the tender mercies of the French and the Japanese fiscal authorities to deduct the cost of your R&D program. That obviously is what happens. You ship the R&D overseas. Is that in U.S. interests? It may well be, in many cases, in the interest of the individual corporation, because of their negotiating ability with foreign governments, but is it in the U.S. national interest? That is the sort of question that seems to me to be one.

The other examples I cited of where you indeed have already shipped a number of pharmaceutical plants. Actually, in the pharmaceutical field a lot of R&D has been shipped overseas partly because of the speed of the regulatory process in other countries to be closer to them with the R&D, partly because of this rule 861 and partly because of the interstate commerce interpretation on the shipment of the drug so you can't supply a foreign market, they have shipped plants as well. But shouldn't it be possible to when you have so many things which I think in many cases run counter to what almost anyone would feel would be good policy?

Mr. RITTER. Are you advocating a new interagency think tank group that reports to the President? I mean, so many of these things have been attempted, and they seem to trip over the same obstacles time and again.

Mr. DIEBOLD. What I was hoping to stimulate was this committee would focus, I really believe you can't talk about science policy today, without focusing internationally and without looking at the mechanisms for applying the science to the society, because it is that interplay. The science, the way the science is done has been affected materially by that. You can't separate science and technology. They are very deeply intertwined. Information technology extraordinarily so. I think—I was trying to stimulate the idea maybe this committee could focus a bit on that whole mechanism.

The whole interplay of institutional relationships are so vital in this area. You cannot focus only on the laboratory. You have to focus on the problem of getting these things to market and the interplay back to the laboratory, and where we go, because also to have any kind of reasonable domestic science policy seems to me you need constant feedback to the—over what does society need, what does the American society need, in order to be able to remain healthy and to remain competitive. We are in a, you know, a horrible position with regard to our balance of trade, and it is only in part due to the dollar. It is in part due to a lot of other factors.

Mr. **Ritter**. I appreciate your testimony, I think it is obvious that what you are saying, we have the flow of information far outpaces our institutional abilities to use it properly.

Mr. **Diebold**. I think, you, know, it was the cartoon character who said we have met the enemy, and he is us. I think that a lot of this is unnecessary, and is something we could have while we were rich and fat and relatively invulnerable to international competition. We aren't any longer. We are a debtor Nation increasing at a greater extent. We are in a highly competitive world, and a lot of the American ability to compete is wasted on not having a whole lot of this really unnecessary antagonism between the business and the public sector is an important element in it, and I think that is probably as much due to both sides, but it is a nonetheless reality.

There is an awful lot of conflicting regulation and conflicting legislation, and it does seem to me unnecessary, and I think that is going to have more to do with America productivity than—or as much to do with American productivity as many of pure science questions.

Mr. **Slaughter**. No questions.

Mrs. **Meyers**. I am sorry that I was late, but just from the question and answer in your comments since I got here, I think you have focused on what—is that our problems are a result of the relationships between Government and business, and the conflicting relation, regulation, the conflicting laws, force a lot of our research and development overseas and create some of our own problems for us essentially; Is that what you are saying to us?

Mr. **Diebold**. That is one of the points I was making.

Mrs. **Meyers**. And, well, elaborate on that. Would that be the main problem as you see it?

Mr. **Diebold**. Well, I think what I was trying to say was I think that equally important to doing high-quality basic science is the problem of getting that information, that science, those insights, used applied by the society, and that in institutional relationships involved in that should be a proper focus of this committee's deliberations on what science policy ought to be about. I think there is a web of often conflicting incentives and disincentives in this area, and that is unnecessary.

Mrs. **Meyers**. OK, I heard you make that point, too. So thank you very much.

Mr. **Brown**. I won't belabor you with additional questions, but I do sense a very important message in what you have said with regard to our overall national productivity and the significance of catching up our policy process with our technological capabilities, and unleashing some of the productivity improving powers of competition with regard to the rendering of a lot of Government services. It is a message that conceivably could result in the development of a consensus within this committee, since it meets the objectives of all parts of the ideological spectrum in many important ways.

Thank you very much for your appearance here this morning.

Mr. **Diebold**. Thank you, sir. We hope we can keep in touch with you.

PANEL

Mr. **Brown**. Next, we will call on the three members of the panel, Dr. Langridge, Dr. Vanden Bout and Dr. Armelagos, if I got the names anywhere close to being right, and we will look at more specifically the utilization of information technologies in the actual pursuit of science.

Dr. Langridge, do you want to start?

STATEMENT OF DR. ROBERT LANGRIDGE, PROFESSOR OF PHARMACEUTICAL CHEMISTRY AND BIOPHYSICS, UNIVERSITY OF CALIFORNIA, SAN FRANCISCO, CA

Dr. **Langridge**. Yes, thank you very much.

I am very honored by the invitation, Mr. Chairman. Rather than addressing the more general problems, which we have had in the earlier testimony. I will describe some of my own experiences, which I hope will illuminate some of the questions facing the committee, particularly some of those in this December 1984 report, the agenda, and I will try to respond to the letter of invitation from the committee, which stated: "You might, for example, help us understand the way in which problems are conceived theoretically, or hypotheses are tested, through the use of computer intensive methods."

Computer graphics is one of the most explosively developing fields within all of computer science and technology, and in science, no matter how fast the supercomputers are, blinding speed is of little use without illuminating interaction. It is computer graphics that provides that interaction.

A major meeting of the computer graphics field, Sigra, was held in San Francisco recently. It attracted over 25,000 people, compared with a few hundred only 10 years ago.

Time Magazine reported in the August 5 issue on this meeting, and I think you have had access to this report. It covered a wide range from TV and movie productions to architecture, flight simulators, but I will concentrate on that part of the field which are the most familiar, to quote Time Magazine, "perhaps the most dramatic use of the technology is in the design of new chemicals and drugs."

The Time Magazine article, although well written and illustrated, suffers from the limitations of static and very two-dimensional pages, so at this point I would like to introduce a quotation from another one of the media, specifically from TV. It is an extract from the NBC Today Show dated 5 years ago, 1980.

With your permission, I would like to just run that. It is only about a 1½ minutes.

[Whereupon, a short video film was shown.]

Dr. LANGRIDGE. As I said, that report is dated 1980, and as the report of Bob Bazell said, the technology was beginning to be used by a number of drug companies.

Now, most of the major pharmaceutical houses have this kind of equipment and, in fact, that graduate student, Jeffrey Blanet, who was seen in that report, is now with the DuPont Corp., engaged specifically for this work in biomedical research.

I should note that at that time, which was the late 1960's, it was by no means obvious that this kind of thing was going to be of any use to molecular biology and pharmaceutical chemistry generally. In fact, the people in that field thought that the computer and the computer graphics in particular weren't very important.

The major credit for encouraging and supporting this development, which is now so widely recognized, must go to the Division of Research Resources at NIH and in particular to Dr. William Raub, who directed the biotechnology resources program and is now responsible for the entire extramural research program at NIH.

The biotechnology resources program is based on the concept of shared resources, that is, the funding of central facilities, not only equipment, but also very importantly support personnel, maintenance, of a magnitude which could not be justified by individual research grants.

Those facilities include many major scientific techniques and are available to research projects from around the country, even around the world.

Due to the support and encouragement of Dr. Raub, in the late sixties and early seventies, several computer graphic research resources were established at Columbia with Professor Levinthal, at Washington University in St. Louis with Professor Cox, and at the University of North Carolina with Professor Brooks, and my own facility, then at Princeton University, and moved in 1976 to the University of California. I should incidentally mention a similar very powerful facility was established by NIH itself under Richard Feldman at the intramural research labs out in Bethesda.

The Division of Research Resources, now under the direction of Betty Pickett at NIH, and the biotechnology resources, directed by Suzanne Stimmler, at NIH, continues to have an impact across all NIH categories out of proportion to its funding, which is about the smallest line item in the NIH budget.

Remember that under Dr. Raub, the Division first saw the significance of molecular graphics and without their active support, this field would not have nourished and spread to the extent that it has today, where it is an integral part of both the University and the industrial research in a variety of fields. At my last count, there were something like 150 facilities around the world.

Now, we were talking earlier about the pluralistic support, and on page 26 of the agenda you have the question, "Is pluralism of many support agencies working effectively in practice?" I have already mentioned that our own support, through ARPA, NIH, and NSF in the early days was very effective. I would like to give an example, a recent example of my own research, where I think it illustrates where some kind of pluralism and support rather than a monolithic support is important.

For a long time, I have been interested in the applications of artificial intelligence, and in the late seventies, one of our students, Bob Abarbanel, became very interested in the application of these methods to protein structure, and we used our already-existing facilities, in collaboration with my colleague, Irwin Kuntz, at the University of California. It soon became obvious that we needed facilities specifically for this purpose.

There are specially designed machines to run these programs called Lisp machines, and in the renewal of the NIH Research Resource Project I included this as a line item. Now, the peer review group appointed by the Division of Research Resources at NIH to evaluate their work consisted, as it always does, of peers from around the country, to evaluate the work. They approved the work in general, but deleted specifically the initiative in artificial intelligence, saying it was "premature."

Let me make it clear that this has probably reflected the views of my colleagues in my own field from around the country. I must emphasize that I have been a member of these peer review groups, and I am strongly supportive of them. I think this is the fairest system yet devised, in spite of the fact that I think in this particular decision, they were wrong. Fortunately, because of the pluralistic nature of these support agencies, I am in a position to prove them wrong, or right, as the case may be, I suppose, thanks to one Federal and one private agency.

About the same time that I submitted that NIH proposal, I also submitted proposals to the Defense Department for the first of the congressionally-inspired round of funding for university research equipment, and also to the Guggenheim Foundation for a fellowship to work on artificial intelligence with Professor Edward Feigenbaum at Stanford. Both were funded, and we have made rapid progress, and Dr. McMarin of the Office of Naval Research has encouraged us to do further work for the Defense Department support. Meantime, the Division of Biotechnology Resources, under Dr. Stimmler, also demonstrated considerable flexibility in response to these changed circumstances. When the outside peer review group described their proposal as premature and specifically deleted these funds, she couldn't simply reverse the decision. But this year, in response to a demonstrated success, and to the recommendation of their own advisory committee, which incidentally is mandated by the biotechnology program, for advise to us and to the NIH, Dr. Stimmler permitted funds to be transferred within her budget specifically to support this work.

I want to underline I cannot overemphasize the difficulty of pursuing this kind of work, a new line, effectively, if the first decision was the only decision. It is very important to be able to pursue various lines of support, certainly for university research.

I would like to return briefly to the Time Magazine article in a different aspects of computer graphics, and they describe, and I quote:

> From the graphics meeting, a 3-minute film sequence produced at Lawrence Livermore Laboratories showed in a few seconds what biology teachers have labored

for years to make clear, the precise mechanism by which molecules of DNA fall upon themselves and form fixed strands of chromosomes.

I have a second videotape—this is silent, so I will talk over it and run it to show what kind of graphics can be done if you have many hours of computing available to you to make just a short film.

This took several hours of computing, and it was not done at Lawrence Livermore, it was in fact done by Dr. Nelson Max, who was on leave from Lawrence Livermore working with Fijitsu in Japan. We made this film for the science exposition at Tsukuba.

In contrast to these earlier films in which there was real time—real time in a sense means that each image that I showed you previously took one-thirtieth of a second to calculate—these images, this whole short sequence, which is less than 2 minutes, took several hours, in fact hundreds of hours, of computation on a very fast computer. What you are seeing here is the DNA molecule as it disappears off into the distance.

In this Tsukuba pavilion in the science exposition in Japan, this was in stereo, you could see it in three dimensions, and the work that we do in real time is also viewable in stereo. It is a very difficult thing to present to a meeting like this, but you see DNA, the double helix, beginning to fold, it folds around these large groups which are within your chromosomes. You have these proteins which fold the DNA around it. What Dr. Max is illustrating here is a conceptional model for the way DNA might fold and form the much larger structures.

I have tried to illustrate here a different aspect of computer graphics. This is essentially the tutorial aspect of being able to teach students and, of course, research workers what is going on with a model which would be practically impossible to build, as said by Bob Bazell in the NBC report, in the real world, certainly impossible to produce like this.

As I said, Dr. Max took over a year with Fijitsu in Japan to produce this, and most of the work that I have discussed and the work related to the drug industry is mostly of the kind in which you actually sit at the console of the computer, interact with the pictures on the screen, rather than to create these over a period of years, and view it as a film. This we would call illustrative graphics rather than interactive graphics, which you get some idea of the way DNA molecules begin to fold up. Finally, this folds up to form a chromosome.

There is one other aspect, I have addressed the pluralism, there is one item which hasn't been spoken to previously, and on page 12 of the Agenda, item 2, you have:

"To what extent is government support of science comparable to government support of the arts and humanities," and I quote, "apart from the value, science is a major contributor to technological innovation."

It is frequently noted that government should support research for the same reasons that it supports the arts and humanities. And I think computer graphics, I hope you will agree, is not only a valuable scientific tool, it also provides in some ways a bridge between the sciences and the arts, and I am quoted in the Time Magazine article as saying that I regard it as computer assisted insight, and I think it is very important, it just isn't a producer of numbers, it is a producer of insight into what is going on.

In 1983, we submitted a short paper to Science on a new computer algorithm we developed, which happened to be 100 times faster than the ones done, but also submitted a computer graphic visualization of the end view of DNA, and each of you have a copy of the final cover.

The end view of DNA is here viewed on the computer graphics. It looked to me like a very beautiful rose window. So I submitted it to them with a picture done by my colleague, Dr. John Grupenhoff of Potomac, MD, which he had taken of the Washington National Cathedral. Artistically, they are both beautiful. That tenfold window at the Washington National Cathedral is at least equal of those in Charte where were built about 750 years ago. It was designed and built in 1977. The same tenfold. Even more remarkably, since DNA is the genetic material, carries the genetic code from one generation to the next, this window up here, also has the same tenfold asymmetry and illustrates the first chapter of Genesis, the creation. I think it is a rather nice parallel.

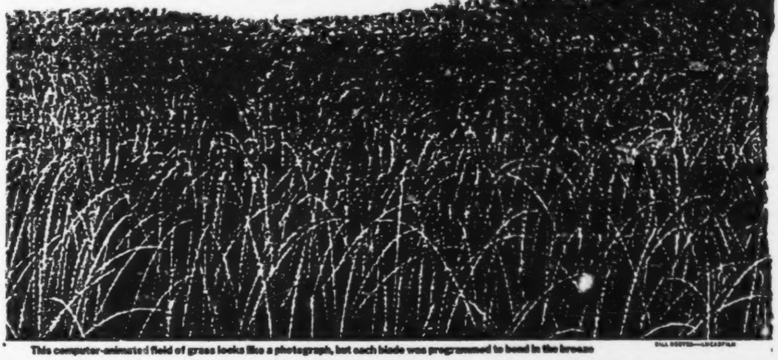
Incidentally, they accepted this paper for publication in March and said they would be delighted to put these pictures on the cover provided we waited for the Christmas issue, so if you look at the date it is December 23, 1983.

Thank you, Mr. Chairman.

Mr. BROWN. Thank you very much. We are inspired to think that this may be the mechanism by which science and art are finally united.

Dr. LANGRIDGE. I hope so. They should never have gone apart.

[The articles follow:]



This computer-animated field of grass looks like a photograph, but each blade was programmed to bend in the breeze

BILL REEVES—LUCASFILM

Artistry on a Glowing Screen

The new, natural look in computer graphics

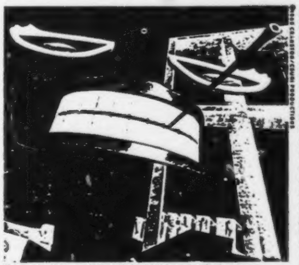
A field of grass sways in the wind, each blade clearly defined in yellow and green. A molecule of DNA, its 65,000 atoms represented by gleaming spheres, twists and folds into a thick, knotty ring. Oversize baseballs zoom by at impossible speeds, trailed by surrealistic soda fountains and eerily chattering teeth.

These remarkable images, as sharp as photographs, yet as free from the bounds of reality as an animated cartoon, were crafted not by humans but by computers. They were among the 35 video and film clips showcased last week at the twelfth annual gathering of the Association for Computing Machinery's Special Interest Group on Computer Graphics (SIGGRAPH), the equivalent of the Academy Awards for 25,000 artists, programmers and electronics engineers involved in the complex business of making computer art.

For two nights, the wide screens at San Francisco's Moscone Center glowed with some of the most sophisticated computer animations yet produced: TV commercials that showed Chevy vans floating in clouds and Norelco shavers zipping around a racetrack; television network logos replete with spinning globes and sparkling call letters; scientific simulations displaying molecules at magnifications no microscope could achieve; and animal, vegetable and mineral objects more realistically portrayed than ever before. Says Computer Artist William Reeves of Lucasfilm, who created the image of windblown grass he calls Blowin' in the Wind: "I'm not going to claim it's just like nature, but I'm pushing in that direction."

Indeed, creating objects that have natural-looking textures is one of the key challenges facing computer artists. "It's very easy to make something look smooth, like plastic or ice," says Wayne Carlson, director of production at Cranston/Csuri Productions in Columbus. "What's difficult is to give something the mottled look of bark, leaves or grass." Texture mapping, a computer technique akin to wrapping a photograph of a rough rock around a smooth stone, is one solution to the problem. Another involves the use of a class of equations called fractals. "It's a technology for filling in random surfaces in a way that mimics the way nature is random," explains Lucasfilm Researcher Robert Cook. "You want a rock to look like a rock, a random rock."

Although the results may resemble photographs or surrealistic paintings, the methods used require more mathematics than artistry. A computer artist must consider every aspect of what he wants his finished work to be and translate it into a numerical representation that the machine can comprehend.



©1985 CRANSTON/CSURI PRODUCTIONS

Smooth, shiny surfaces highlight a surrealistic scene

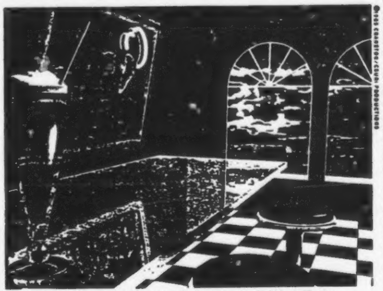
The basic techniques by which this translation is accomplished were laid out in the late '60s and early '70s by two University of Utah professors, Ivan Sutherland and David Evans, in fulfillment of a contract for the U.S. Department of Defense. Their task: to build a flight simulator for pilot training that would show on a screen the same unfolding landscape the pilot would see from the air. To do this, the Utah scientists first had to program into the computer a precise mathematical model of every tree, house and mountain in the flight path. Then they instructed the machine to put each of those objects into three-dimensional perspective, to give it the illusion of depth and to eliminate those surfaces that would be hidden from the viewer's line of sight.

Today's most advanced graphics systems take Evans and Sutherland's procedure one step further. Using a programming technique known as ray tracing, they follow the path of each ray of light as it travels from its source, say the sun, to the viewer's eye. Upon striking a surface, each ray will be absorbed, reflected or transmitted in accordance with the laws of optics. Programmed with a mathematical model of the behavior of light rays, the machines can re-create lighting effects of dizzying complexity. Caltech's Jim Kajiya, for example, has used ray tracing to show how ripples travel through a reflecting pool.

Once the color and intensity of each point of light have been calculated, those data are converted directly into the pixels, or picture elements, that make up the images on the computer's screen. Each pixel is either red, green or blue. When viewed from a distance, however, they coalesce like the dots in a pointillist painting. Says Lucasfilm's Cook: "It's like mixing paint. If you stand back, they all blend together."

The whole process consumes vast quantities of computer time. One minute of film may involve as many as 100 billion calculations, driving the costs of TV commercials as high as $4,000 per sec. But conventional filmmaking techniques can be even more expensive. Using a Cray X-MP supercomputer and the latest graphics technology, the special-effects team at Digital Productions was able to create the battling spaceships in the film *The Last Starfighter* for $4 million. To produce the same scenes with scale-model miniatures would have cost $12 million to $24 million.

With bit parts in such movie hits as *Ghostbusters* and *Amadeus*, computer graphics has become part of the standard repertoire of filmmakers and art directors. But the technology is not restricted to Hollywood and Madison Avenue. The Defense Department has invested heavily in complex simulators that use computer graphics for training personnel in the use of tanks, jets and submarines. In the simulators that help teach pilots to fly the CH-53 Sea Stallion helicopter, the computer graphics alone can cost $3 million.



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Neon lights and a ground-glass bar display complex lighting effects

The technology is fast spreading to other professions as well. By mathematically building their scale models within a computer, architects can see what large buildings will look like from the ground, the air or the window of a high-rise across the street. Petroleum engineers can explore graphic versions of geological formations thousands of feet below the ocean floor without drilling. Physicians, manipulating the images produced by CAT scanners, can visually probe the brains of patients without having to perform exploratory surgery. Says Don Greenberg, director of computer graphics at Cornell University: "It's like having a doctor walk on the inside of the skull."

Perhaps the most dramatic use of the technology is in the design of new chemicals and drugs. By showing how the molecules of the active ingredients in a drug attach themselves, like keys in locks, to target molecules in the body, computer models can help researchers see how a change in molecular structure will affect a drug's behavior. Says Robert Langridge, who heads the computer-graphics laboratory at the University of California, San Francisco: "I call it computer-assisted insight."

Last week's SIGGRAPH attendees got a taste of that insight during a 3-min. film sequence, produced at Lawrence Livermore Labs, that showed in a few seconds what biology teachers have labored for years to make clear: the precise mechanism by which molecules of DNA fold upon themselves to form thick strands of chromosomes. "It's something you could never do with a camera," says Livermore's Nelson Max. The audience at SIGGRAPH greeted his technological tour de force with enthusiastic applause.

But the biggest ovations last week were reserved for a more subtle use of computer-graphics technology: a touching, 5-min. animation titled *Tony de Peltrie*. Created by a design team from the University of Montreal, it depicts a once famous musician who sits at a grand piano in the middle of a hardwood floor, tickling the keys and tapping his white leather shoes to the beat of his memories. In striking contrast to the awkward, robot-like characters in earlier computer films, De Peltrie looks and acts human; his fingers and facial expressions are soft, lifelike and wonderfully appealing. In creating De Peltrie, the Montreal team may have achieved a breakthrough: a digitized character with whom a human audience can identify. —*By Philip Elmer-DeWitt.*

Reported by Thomas McCarroll/New York and Dick Thompson/San Francisco

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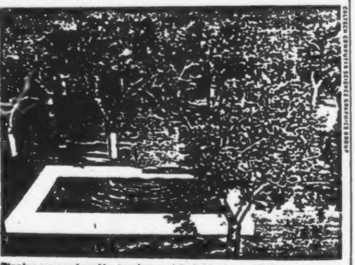
Digitized baseballs give NBC Sports the high-tech look



CALTECH COMPUTER SCIENCE GRAPHICS GROUP

Ripples are rendered by tracing each individual ray of light

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Supercomputers Helping Scientists Crack Massive Problems Faster

New high-powered number crunchers popping up in computer centers across the U.S. are attracting more theoretical chemists and extending the range of problems that can be solved effectively

Ron Dagani, C&EN Washington

In 1978, Charanjit S. Pangali, then a graduate student working with chemical physicist Bruce J. Berne at Columbia University, composed a computer program to solve a difficult problem in statistical mechanics. Simply put, they were trying to predict the effect of intermolecular forces on two unsolvated xenon atoms in water. Using a conventional mainframe and a minicomputer, both located on campus, they got their answer, but only after the machines had spent a total of some 500 expensive hours grinding out solutions to a blizzard of equations.

Two months ago, Pangali tried the same problem on a supercomputer. He got the correct answer in 19 minutes.

With performance like that, the supercomputer is quickly becoming the darling of computationally oriented researchers. Its dazzling speed is enabling them to tackle gargantuan problems that, previously, were too time-consuming to even be considered. After all, how many scientists could afford to tie up their institution's mainframe for thousands of hours while it plugged away on a single problem? But with the arrival of the latest generation of supercomputers, such mind-benders often can be cracked in a mere hour or two.

Until now, though, a relatively small number of researchers had access to supercomputers. The few machines that existed were ensconced in a handful of corporate labs—mainly oil and aerospace companies—or in government installations devoted largely to energy and weapons research, intelligence gathering, or the space program.

Academic scientists, in particular, usually found themselves out in the cold. Most universities just couldn't afford the $5 million to $20 million systems. And unless they were involved in problems of interest to the government, most professors had little hope of logging on the prized machines. Some of them, out of necessity, took their research projects to Europe, where supercomputers have been more accessible.

Fortunately, such overseas pilgrimages no longer are necessary. These most powerful of modern scientific computers now are popping up in more U.S. computer centers than ever before. In a move that has generated much excitement, the National Science Foun-

Cray customer engineer Jerry Cavallo briefs Anita Winfield, computer support supervisor at Lawrence Livermore National Lab's magnetic fusion computer center, on the center's new Cray-2 supercomputer

News Focus

NSF guiding supercomputer use to new highs

The year 1986 is going to see an explosion of supercomputer use, says John W. D. Connolly, director of the Office of Advanced Scientific Computing (OASC) at the National Science Foundation. Academic researchers who had been chafing over the general unavailability of supercomputers finally will get their chance to log onto these most powerful of number crunchers.

The big jump in use will come at the five new national supercomputer centers that NSF announced earlier this year (C&EN, March 11, page 14; July 8, page 7). These will be located at the University of California, San Diego; the University of Illinois; Cornell University; Princeton University; and the Pittsburgh Center for Advanced Computing. The last is a consortium consisting of Carnegie-Mellon University, the University of Pittsburgh, and Westinghouse Electric.

To NSF insiders, these five sites are known as Phase II centers, to distinguish them from the six sites, called Phase I centers, where many NSF grantees have gotten their first taste of working with a supercomputer. The Phase I centers, such as Purdue University, the University of Minnesota, and Boeing Computer Services, already owned superspeed machines before NSF's initiative began.

NSF wanted to wedge open the gates to large-scale computing as soon as possible. So, it started buying supercomputer time at the Phase I centers and parceling it out to NSF grantees. The foundation awarded about 5000 hours in fiscal 1985. For the second year of the program, the allocation will be increased to about 8000 hours, Connolly says. Of course, once the Phase II centers come on line in the next seven months, the amount of supercomputer time available will shoot up to about 60,000 hours. That's what Connolly means by an explosion.

As it looks now, whatever demand that develops for supercomputer time will have to be handled largely by the Phase II centers already announced. Because of the unpromising budgetary outlook, NSF is not planning to set up any more Phase II centers in the near future, Connolly tells C&EN. Of course, he adds, if Congress makes more funds available, the number of centers could rise to 10 or 12.

For fiscal 1986, NSF requested $46.2 million for its supercomputing initiative. That's 15% more than it got last year and is, essentially, what Congress gave it in the recently concluded budgetary battle.

NSF plans to spend about $200 million over the next five years on the Phase II centers. These centers will get between $7 million and $13 million apiece each year, depending on their size and scope.

Already, about 400 research groups at almost 100 institutions around the U.S. have received NSF grants involving supercomputer use. About 60 of these groups, or 15%, are involved in chemical research.

Not surprisingly, the areas that account for the bulk of supercomputer use are physics, materials science, chemistry, engineering, and mathematics. In chemistry, researchers use the machines most frequently for computations in quantum mechanics and statistical mechanics. Supercomputers don't seem to have broken into other areas of chemistry where smaller computers are used routinely. No one, as yet, is using a supercomputer to plan organic syntheses, for example.

"Very few experimentalists in chemistry are at the stage where they need a

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dation is helping set up five national supercomputing centers that will be available to scientists in all 50 states.

The increased access to supercomputers is expected to have a dramatic impact on research, engineering, and higher education in the U.S. These computers are extending the range of problems that can be solved effectively. They also are furnishing more detailed, accurate, and realistic solutions to complex problems that previously could be solved only to a crude approximation. Furthermore, many more professors and students now will be getting hands-on experience with supercomputers. People are betting that this will boost the U.S.'s scientific standing in the world.

Although supercomputers are capable of performing hundreds of millions of arithmetic operations per second, they cannot be considered merely hyped-up calculators. Rather, they are machines that can reveal the unseeable and even the not otherwise knowable.

They are helping scientists make discoveries in two key ways. First, by mathematically simulating natural phenomena, such as the birth of a star, which cannot be studied at close hand. And second, by testing hypotheses and simulating experiments that would be difficult or impossible to carry out in the laboratory.

Such simulations can have very practical benefits. For example, by simulating the air flow around an entire airplane on a computer screen, engineers can try out new aerodynamic designs without resorting to time-consuming wind-tunnel tests on prototypes. By charting the flow of reactants and products inside an internal-combustion engine, researchers will be able to design more fuel-efficient and trouble-free engines. And by simulating the circulation of the oceans and atmosphere and the effects of carbon dioxide buildup in the atmosphere, scientists expect to improve long-range weather forecasting.

The great value of such simulations is that they permit researchers "to circumvent some real-world constraints," according to mathematician Bill L. Buzbee and physicist David H. Sharp of Los Alamos National Laboratory. For example, a nuclear reactor accident can be played out without risking environmental contamination. Or, a chemical reaction that takes place in the blink of an eye can be scrutinized in slow motion on a graphics terminal.

Among chemical scientists, the supercomputer has been embraced most avidly by the theoretical chemistry community, in whose midst the line between physical chemists and chemical physicists tends to blur.

NSF's Connolly with map showing locations of supercomputers and users

supercomputer," Connolly says. Most experimentalists can get by on their minicomputers. "To really need a supercomputer," he maintains, "you need a super problem."

Researchers apparently have plenty of those, but sometimes they also have a reluctance to give the supercomputer a try. That's because the machines are regarded as hard to use and hard to access, Connolly says.

At present, there's some truth to this. One difficulty can be adapting software. "A code written for a Vax is not necessarily going to make the most efficient use of a supercomputer," says physical chemist Edward A. McCullough Jr. of Utah State University. "In fact, it may not even work at all without modification," he adds. To capture the speed inherent in vector processing, reprograming is necessary. And when a big program is involved, that can demand an enormous effort.

Another problem that some researchers face is communicating with a supercomputer at a remote location. Not everyone who has to work by long distance has access to a high-speed data communications network. Without one, the user may be forced to talk with the computer via the telephone lines, whose rate of data transmission is inadequate for many purposes.

A case in point is Columbia chemistry professor Bruce J. Berne, who has, been using the University of Minnesota's supercomputer from New York City. He found the telephone lines much too slow to handle the large amounts of data he needed to get back from the machine. So instead, he has data-crammed computer tapes mailed to him by Federal Express.

Users of the Phase II centers likely will have an easier time communicating with the supercomputers. NSF is planning to plug all these centers into existing networks such as BITNET and the Defense Department's ARPANET, and to upgrade their data-transmission capabilities. Eventually, NSF also hopes to set up its own nationwide data network. But, says Connolly, it's not yet sure what form it will take.

These practitioners often specialize. For instance, chemical kineticists look at how bonds break and form during chemical reactions. Researchers in quantum mechanics explore the electron-energy-level structure of atoms and molecules. And researchers in statistical mechanics try to predict the properties of bulk matter from a knowledge of the interactions of individual molecules. To do this, they model the conformations and interactions of everything from simple molecules to proteins, polymers, and DNA.

To gain insights into these aspects of chemistry, researchers often must solve incredibly large families of complex equations. The more equations, the more arithmetic operations must be carried out, and the more time it takes.

Supercomputers are made for such problems because they can do more flops, or floating-point operations per second, than conventional computers. The Vax 11/780, a minicomputer widely used in scientific research, can run at about 500,000 flops. The Cray-1, a supercomputer introduced in 1976, can crunch numbers 100 times faster. This machine no longer is in production: it was superseded earlier this year by the Cray-2, which is six to 12 times faster than the Cray-1. In fact, the Cray-2 boasts—although in practice it never reaches—a top speed of 1.2 billion flops. This is 40,000 to 50,000 times faster than a personal computer.

Computing speed, though, is not the only feature that makes a computer super. Internal memory capacity also is crucial because if the memory isn't large enough, the programs and data necessary to solve large, complicated problems can't be loaded into the computer efficiently. The $17.6 million Cray-2 leads the pack here, too, with more internal memory capacity than any other computer in the world—256 million 64-bit words, or 2 billion bytes.

The unimaginable speeds and capacious memories of today's supercomputers were made possible by innovations in silicon chip and computer design. Miniaturization, dense packing of components, and faster circuits are the key. In the Cray-2, for example, 240,000 computer chips are squeezed into a C-shaped cabinet 53 inches across and 45 inches high. Packing chips so close together minimizes the time necessary for electric signals to travel from one part of the machine to another. Similarly, the increased density of integrated circuits has cut the time computers need to perform each cycle of logical operations.

Aside from these aspects, supercomputers are special because they process information differently than do conventional machines. Most computers have a single processor that operates sequentially on only one arithmetic element at a time. This is known as scalar processing. Today's fastest supercomputers, on the other hand, contain two or more identical processors, each of which can operate on many similar data items at the same time. These vector processors, as they are called, can, for example, multiply two 100-element arrays in a single operation. A scalar processor given the same problem would plod along by performing 100 sequential multiplications.

Parallel processing—the coupling together of several processors—allows a big problem to be solved faster by breaking it down into more digestible pieces. Thus, the Cray-2's four main processors can work on different parts of a problem simultaneously.

With multiple processors zipping through calculations at breakneck speed, the output of numbers can easily overwhelm the researcher. "There's no way to understand those numbers unless you get pictures," says molecular biologist Robert Langridge. He and his coworkers in the department of pharmaceutical chemistry at the University of California, San Francisco, have been using computer graphics to visualize the movements of molecules in three dimensions and in time. Their goal is to understand such dynamical processes as conformational changes in polypeptide chains or the docking of a drug molecule with a receptor site.

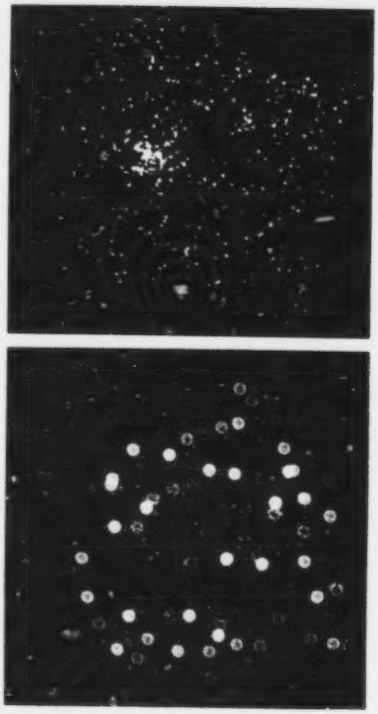
Graphics also are vital for fleshing out such quantum mechanical concepts as molecular orbitals, says David A. Pensak, who supervises computer science research at Du Pont's central research department in Wilmington, Del. As an example, he notes that one can calculate what a ground-state molecule's orbitals look like after the molecule accepts an electron and is boosted into an excited state. But, he says, the calculation alone "would never give you a feel for how the orbitals change during the acceptance process."

The electronic structure of molecules can be discerned by solving the Schrödinger equation, which is central to quantum mechanics. At the National Aeronautics & Space Administration's Ames Research Center in California, supercomputers are helping scientists get better solutions to this formidable equation. Those solutions then can be used to predict molecular properties such as bond lengths and dissociation energies.

Recently, chemical physicist Harry Partridge and his Ames colleagues developed a method that allows them to calculate the dissociation energies of simple ionic molecules to an accuracy of 0.1 eV. Dissociation energies for such compounds, Partridge notes, are difficult to get experimentally, yet they're crucial to an understanding of metallic chemistry.

Access to supercomputers has allowed theoreticians to deal more rigorously and realistically with other difficult problems that, previously, could be solved only inadequately or incompletely.

Their understanding of the structure of water, for example, has been honed with each new jump in computing capability. Scientists' fascination with water derives from its unusual properties, both in pure



A computer simulation (top) shows a solvated electron (red) floating in liquid water. The blue crosses represent the positions of the oxygen atoms of 214 water molecules, which comprise the unit cell. "Holes," or vacant regions, are scattered throughout the hydrogen-bonded network of molecules. The electron's probability cloud (the volume in which the electron is most likely to be found) is represented quantum mechanically as a chain of overlapping spheres coiled inside a cavity in the liquid. The bluish-white stars within this cavity are artifacts of the graphics process. In a closeup view (bottom), the blue pointillistic cloud (the electron's region of delocalization) is surrounded by the first shell of solvating water molecules (oxygens are red, hydrogens are bluish-white). The water molecules appear smaller than they actually are. The calculations necessary to produce these images were done on a Cray-1 supercomputer located at the University of Minnesota. Pictures were generated using a graphics program at Columbia University by graduate student Anders Wallqvist, working with Columbia chemistry professor Bruce J. Berne and postdoctoral research associate Darjan Thirumalai form and as a solvent, and from its importance to biological and industrial processes.

In the early 1970s, physicist Aneesur Rahman of Argonne National Laboratory and chemist Frank H. Stillinger of AT&T Bell Laboratories used a mainframe to simulate the structure of pure water. Because of the speed limitations of their machine, they had to treat the oxygens and hydrogens of the water molecules as classical particles obeying Newton's laws of motion.

Today, the supercomputer enables researchers like Columbia's Berne to carry out quantum-corrected simulations, in which the wavelike properties of the particles are considered. This kind of treatment, Stillinger says, has led to a much more complete and realistic picture of the three-dimensional architecture of hydrogen bonding in liquid water.

But until last September, Berne had no way to log on a supercomputer. Then NSF's Office of Advanced Scientific Computing came to the rescue and gave him a grant of time on the University of Minnesota's supercomputer.

With additional support from NSF and the National Institutes of Health, Berne has been probing the structure of water using Monte Carlo simulations with a quantum twist. This method is so named, he explains, because it's like a game of chance played out on a computer: The machine selects, seemingly at random, positions for all the atoms in a large assemblage of water molecules. In fact, the atoms' positions are chosen so as to conform to a precise probability distribution based on the potential energy at those positions. Ideally, the computer would pick positions an infinite number of times and then average all of them to get an accurate picture of the preferred arrangement of the water molecules. Even a supercomputer can't do this. But it does approximate this process and so provides more true-to-life answers than slower machines could.

Recently, Berne and his coworkers have been looking at how an electron is solvated in water. "An electron is so light that it's basically just a quantum mechanical particle," he says. "There's just no way that a classical treatment of it will give you any meaningful results."

Using the Minnesota supercomputer to do the calculations and Columbia's chemistry graphics facility to take the snapshots, they have opened another window into an unseen quantum mechanical world. When the electron is put into water, Berne explains, "it digs a cavity for itself, a cavity larger than the water molecule itself. And then the waters around it point their hydrogens in towards it, forming an interesting structure." Without a supercomputer, he adds, they could never have visualized this scene.

Stillinger, meanwhile, has been pursuing even more demanding structural problems using Bell Labs' Cray-1, which was installed there in 1980. He and coworker Thomas A. Weber are visualizing complex materials such as liquid sulfur, amorphous nickel/phosphorus alloy, and silicon in its crystalline, liquid, and low-temperature amorphous phases. Echoing Berne, Stillinger says that to try to do these studies before the advent of the supercomputer "would have been a totally frustrating experience. You wouldn't have learned anything worthwhile."

Researchers also are using supercomputers and statistical mechanics simulations to probe how chemical reactions take place. In one such study at Purdue University, theoretical chemist William L. Jorgensen and coworkers Jayaraman Chandrasekhar and Scott F. Smith focused on a simple, well-known halide-exchange reaction in aqueous solution. A chloride ion attacks methyl chloride, displacing one of the chlorines.

The rate of this reaction—and therefore its free-energy profile—is strongly affected by the solvent being used. The reactants and transition-state species are always surrounded by solvent molecules. The relative degree to which these species are solvated influences the height of the energy barrier that must be traversed in going from reactants to products. Thus, in any simulation, the solvent molecules are going to play a crucial role in the energetics of the reaction.

The Monte Carlo calculations for this problem were done on Purdue's Cyber 205, a supercomputer made by Control Data Corp. This machine is roughly comparable in computing power to a Cray-1.

The reaction profile the Purdue researchers calculated held no surprises—it was essentially what chemists had expected. Nonetheless, their result is significant, Jorgensen points out, because it is "the first time that anybody has been able to calculate from first principles the free-energy profile for a [mechanistically] complex organic reaction in solution."

Jorgensen expects that further studies of this type will, in the long run, enable theoretical chemists to reach their goal of learning how to predict the rates of chemical reactions in solution.

The simulation of the methyl chloride reaction was done piecemeal over a period of two or three months because it required about 50 hours on the Cyber 205. The alternative, Jorgensen says, would have been to "tie up a Vax for 24 hours a day for six months to a year."

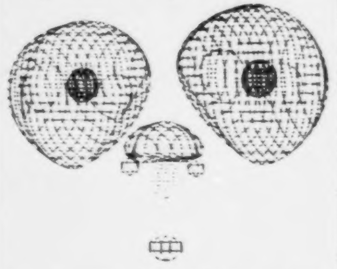
Even so, Jorgensen isn't blessed with limitless access to Purdue's supercomputer. Although the university has been generous with allocations of supercomputer time, he doesn't want to wear out his welcome. "I really can't expect to get more than, say, half an hour a day on the Cyber," he says.

So when the Purdue researchers wanted to extend their studies of the methyl chloride reaction into an aprotic solvent, namely dimethylformamide (DMF), they decided to perform the new calculations on a Gould superminicomputer located in Jorgensen's lab.

On the Gould, the DMF calculations were completed in less than two months and provided an interesting and unanticipated result: In DMF, unlike in water, the reaction is a two-step process in which the reactants form a complex prior to the rate-determining step.

Thus, even though super-speed computers are coming into broader use, they certainly are not sweeping their less-powerful cousins into the dustbin. Rather, supercomputers are taking their place in the spectrum of different computer systems that chemists rely on.

Computer shows BaH_2 molecule is bent



A computed electron-density contour of the $3a_1$ molecular orbital of barium hydride (BaH_2) shows the molecule is bent. This took scientists by surprise because, based on their knowledge of two related molecular species, they had expected the atoms of BaH_2 to be arranged linearly. In the diagram, the inner spheres, not drawn to scale, represent the nuclei of barium (blue) and hydrogen (red). The other surfaces enclose the volume in which the electrons are most likely to be found. Richard Jaffe and Harry Partridge at NASA's Ames Research Center programed their Cray X-MP supercomputer to perform the quantum mechanical calculations necessary to generate this picture

The rule of thumb, according to Jorgensen, seems to be: "Use whatever [machine] you can get your hands on."

Jorgensen says that the Gould, with about one tenth the speed of the Cyber 205, offers his group "a reasonably cost-effective alternative to using a supercomputer." The Gould's big attraction, though, is that it's available to his group 24 hours a day, seven days a week. Jorgensen bought it with part of the NSF grant money that he receives to support his research.

Opting for a less-powerful but more-accessible system apparently is not uncommon. In fact, Peter Lykos, a professor of chemistry at Illinois Institute of Technology, Chicago, observes that computational chemists "seem to be willing to give up access to large amounts of computing power in exchange for having their own to-have-and-to-hold-and-to-control systems."

Although chemists are excited about their new-found access to supercomputers, there's also considerable interest in intermediate-type machines—those that bridge the gap between superminis and supercomputers. These intermediates, or "Crayettes" as Lykos likes to call them, offer number-crunching power approaching that of a supercomputer, but at a fraction of the cost. For example, Intel Scientific Computers recently introduced a family of computers that it says will provide up to one third the performance of a Cray-1 at about one tenth the cost, or $500,000 (C&EN, Feb. 18, page 31).

Lykos says he would like to see national science policy shift so that scientists "who are happier owning their own machines" could get support for buying such near-supercomputers. At present, these machines are too pricey to permit NSF to fund them through its departmental instrumentation program, which has helped many chemistry departments get state-of-the-art minicomputers.

Near-supercomputers also don't seem to fit neatly into other NSF funding programs, including that of the Office of Advanced Scientific Computing. In the foundation's view, these machines are too costly for a single research group. But according to OASC director John W. D. Connolly, NSF can fund intermediates if they are proposed by an interdisciplinary team. In such a situation, several programs in NSF could share the cost. But that, Connolly admits, "tends to be a little bit awkward." So NSF presently is exploring possibilities for funding these computers through special mechanisms. In any case, he tells C&EN, the issue "hasn't been settled yet."

Although some scientists are satisfied with getting near-supercomputer performance, others find themselves in need of computational power that is beyond anything available today. The fact is, solutions to many difficult problems still are not being computed to the extent required because supercomputers just aren't fast enough. To do these problems justice, scientists say they need machines 100 to 10,000 times faster than the speediest ones available.

To pursue these problems with slower computers would be pointless. For example, scientists would like to make an accurate calculation of the mass of the proton to check the validity of certain theories in high-energy physics. But a machine given this task would have to slog through about 10^{18} arithmetic operations, according to Ray T. Hagstrom, who heads the supercomputer development group at Argonne National Laboratory. The world's fastest computers would need about 50 years to finish the job, he says.

Other problems that are beyond present capabilities involve simulating complex, time-dependent phenomena in three dimensions—for example, magnetic fusion, atmospheric turbulence, and protein folding.

Simulating the behavior of proteins is a stupendous task because these molecules consist of thousands or tens of thousands of atoms. To get accurate results, the equations of motion for each atom must be solved at sequential time intervals lasting fractions of a picosecond (10^{-12} second). As a result, one can only simulate phenomena occurring in time spans far smaller than a microsecond, even on the fastest supercomputers. To study a process that takes a leisurely tenth of a second would require hundreds of supercomputer hours.

Chemistry and physics thus are, in the words of one scientist, "bottomless pits," in terms of their requirements for computing time. Theoreticians will continue to seek ever-faster computers because they always will be able to come up with problems too horrendous for even the next generation of machines.

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An everyday household sponge can be thought of, structurally, as consisting of two components—the sponge matrix and the pore space. Both components interpenetrate one another and are continuously connected. An emulsion consisting of equal parts of oil and water would have a similar structure. If surfactant molecules were present, they would orient themselves into a sheet or surface separating regions of oil from regions of water. Such a surface is shown above in green. It was generated using a Cray-1 supercomputer by graduate student David M. Anderson, working with chemical engineering professors H. Ted Davis and L. E. Scriven and mathematics professor Johannes C. Nitsche at the University of Minnesota. The surface shown here has no "inside" or "outside" —it merely divides space into two interpenetrating, continuous, labyrinthine domains. Each domain is threaded by a tetrahedral lattice. The two lattices are shown in red and blue where the surface itself has been cut away. Such surfaces are being studied as models of structures believed to occur in certain types of liquid crystals, microemulsions, phase-segregated polymer blends, porous catalysts, and other materials of keen interest to scientists

That next generation is on the drawing boards now, and two machines in particular are grabbing much of the attention: Cray Research's as-yet-unnamed successor to the Cray-2, and ETA Systems' ETA-10. Both machines are expected to be unveiled within a year or two. Both also are aiming for a top speed of 10 gigaflops, or 10 billion flops. The "Cray-3" is expected to have as many as 16 processors running in parallel. Its memory may be able to store up to 8 billion bytes of data—four times as much as the Cray-2's. The ETA-10 will harness as many as eight processors. In that configuration, its maximum memory capacity will total 2.3 billion bytes.

Beyond these looms the prospect of computers consisting of thousands of processors, each performing independent operations at the same time. Although they promise unheard-of performance, they also present engineers with serious problems of control, communications, and software.

Nevertheless, a number of visionary computer projects around the world are inching toward that goal of massive parallelism. Japan's National Super-Speed Computer Project, for instance, is working to develop a machine 1000 times faster than present-day supercomputers. In Cambridge, Mass., Thinking Machines Corp. hopes to build a 64,000-processor computer. And that's just a step on the way to their long-range ambition of designing a machine with a million processors. Similar projects are chugging along at, among others, Massachusetts Institute of Technology, the University of Washington, New York University, and California Institute of Technology.

Scientists also are keenly interested in building high-speed computers for specialized uses. Already, customized machines have been developed that can zip through certain kinds of calculations faster than any general-purpose supercomputer. One of these is the array processor, a highly efficient computer designed to manipulate long strings of data in the same way. At Argonne National Lab, for one, scientists are exploring the idea of hooking together dozens of fast array processors to create an even more specialized supersupercomputer.

Similarly, at Du Pont's Experimental Station, researchers are looking into the possibility of assembling a computer system specifically designed to do calculations central to the firm's research efforts. Du Pont's Pensak says his group might achieve this, for instance, by buying commercially available processors and assembling them into networks. Designing their own computer is necessary, he tells C&EN, because computer companies don't make specialized machines unless they think they can sell enough of them to make a profit.

Even as Pensak and his coworkers tinker with alternative computer architectures, excitement is building at Du Pont concerning a more immediate milestone: the imminent arrival of the firm's first supercomputer. Until now, Du Pont researchers had to buy super-speed computing time on other people's machines. But in a few months, it expects to receive its very own Cray-1.

Even though it's not the latest model, it will bring Du Pont the substantial benefits of having a high-powered number cruncher on the premises. Pensak, at least, is sure of one thing: "Once our scientists get their hands on this machine," he predicts, "they're going to find ways to use it that we've never even dreamed of." □

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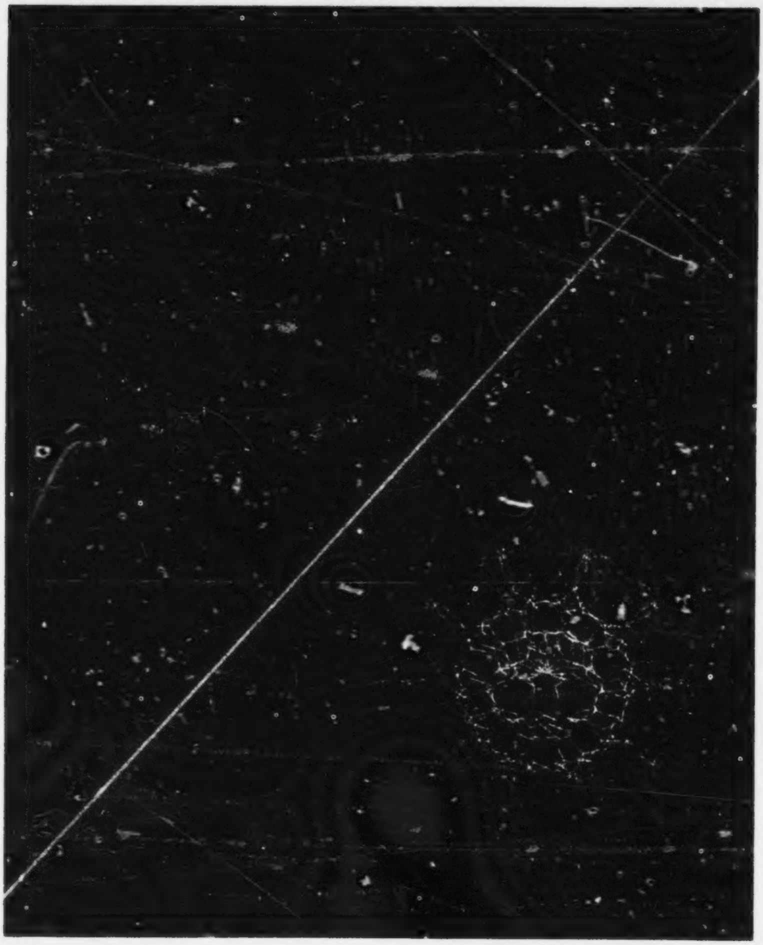

COVER

(Top, left) West window of Washington Cathedral, Washington, D.C., designed by Rowan Le Compte in 1977, depicts the first chapter of Genesis (the creation). [Photo by John T. Grupenhoff, Potomac, Maryland] (Bottom, right) Computer graphics-generated axial view of tenfold, B form DNA [R. Langridge *et al.*, *J. Mol. Biol.* 2, 38 (1960)] using a new, fast surface algorithm. See page 1325. [Computer Graphics Laboratory, University of California, San Francisco 94143]

Van der Waals Surfaces in Molecular Modeling: Implementation with Real-Time Computer Graphics

Abstract. *A method is described for generating van der Waals molecular surfaces with a real-time interactive calligraphic color display system. These surfaces maintain their proper representation during bond rotation and global transformations, and an interior atom removal method yields a comprehensible picture of the molecular surface for large molecules. Both algorithms are faster than previous methods. This combination provides a powerful tool for real-time interactive molecular modeling.*

Molecular modeling with interactive color computer graphics in real time is a powerful method for studying the structures of molecules and their interactions (*1–3*). Computer-generated skeletal models maintain a consistent representation during manipulations such as bond rotations and global transformations but have the disadvantage that they give no indication of the physical space occupied by the atoms. We describe here a method for representing molecular surfaces that, unlike previous methods, is suitable for real-time interaction and manipulation.

With raster graphics atomic surfaces may be represented by shaded colored spheres. The displayed molecular surface is constructed by removing hidden surfaces of intersecting and overlapping spheres (*4, 5*) and shows a molecule in a given orientation and conformation. To view the molecule from another angle or in another conformation, one must generate an entirely new surface. Because hidden surface elimination may take several minutes on present equipment, this representation is of limited use in real-time molecular modeling. Several methods based on line drawing displays are available for similar static hidden-line representations (*6*). Other methods are based on an original idea by Richards (*7*) in which a "solvent-accessible surface" is traced out by the inward-facing surface of a "solvent sphere" making contact with the van der Waals surface of atoms in the molecule. This was first developed for studies of molecular interactions by using an interactive monochrome display (*8*), and later extended (*9*) for an interactive color display by using dots to represent the exterior solvent-accessible surface and internal cavities. A similar molecular surface may be generated more rapidly by using a "bit" lattice (*10*). Although these surfaces (*8–10*) may be globally manipulated in real time, bond rotation still requires recalculation of the area affected by the change. Therefore, modeling with molecular surfaces of this variety and frequent changes in torsion angles is laborious.

We have developed a method that generates a molecular surface faster than the above method and which has the significant advantage that the space-filling representation is retained during interactive real-time bond rotation. The ability to change the conformation of the molecular surface in real time cannot be overemphasized (*11, 12*).

For each atom surfaced, we generate a set of points distributed uniformly over a sphere whose radius is the van der Waals radius of the atom. Each point is compared against the spheres associated with each connected atom and discarded if it lies inside any other sphere. This conceptually simple algorithm produces a precise representation of the van der Waals surface of a molecule (13) and is displayed and manipulated interactively in real time.

These surfaces are well suited for molecules of about 100 atoms or less, but the inclusion of all interior atoms and their surfaces for a large molecule, such as a protein, produces a confusing image. Hence, we invoke another procedure for the removal of interior atoms. We use a bit lattice similar to that described by Pearl and Honegger (10) and map the coordinates of each atom onto a discrete three-dimensional Cartesian grid. The extent of an atom is represented by a cube of 3 by 3 by 3 grid points, the center of the cube corresponds to the center of the atom. The distance between adjacent grid points is typically chosen to be 1.6 Å. Grid points that represent atoms are considered occupied and all others unoccupied. To select interior atoms, the grid is searched in each orthogonal direction to determine the surface grid points, defined as those occupied grid points adjacent to unoccupied ones. An atom that has no surface grid points associated with it is defined as an interior atom (14). A van der Waals surface is then generated for each selected surface atom to produce the molecular surface.

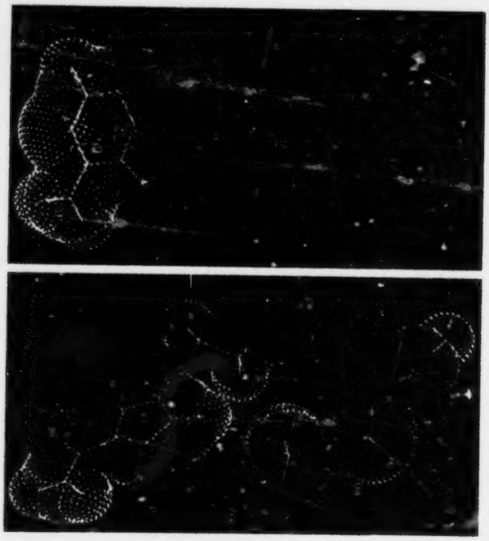

Fig. 1. (top) Van der Waals molecular surface of ATP, shown at a density of 25 dots per square angstrom. The surface is color-coded by atom type: carbon (green), nitrogen (blue), oxygen (red), and hydrogen (white). (bottom) The same surface after real-time rotation about the glycosyl bond.

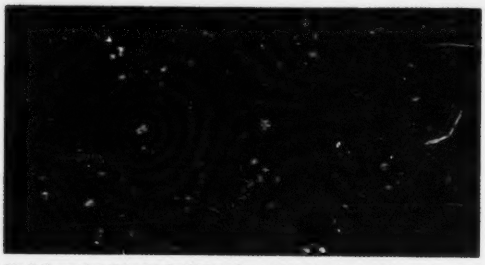

Fig. 2. Stereo view of the van der Waals surface of the noninterior atoms in a section of the active site of dihydrofolate reductase (blue dots), the skeletal model of the residues in the active site (red lines), and the methotrexate molecule and its van der Waals molecular surface (green lines and red dots).

The entire surface of a large molecule is usually not required when modeling interactions with other molecules, such as binding of drugs to receptors. We select a site by searching for atoms in a molecule within a given distance from a defined set of coordinates in the region of interest. Interior atom removal is then invoked and atoms selected both as site and surface atoms can be displayed.

Figure 1 shows the skeletal model and the van der Waals surface of adenosine triphosphate (ATP) (15) in two different conformations. The surface dots are color-coded by atom type, and their density is chosen as 25 dots per square angstrom to illustrate the features of the surface. This surface maintains an accurate space-filling representation during bond rotation. It should be emphasized that the bond rotations shown in Fig. 1 were performed in real time without recalculation of the surface.

To illustrate molecular interactions, a section of the active site of dihydrofolate reductase occupied by the antineoplastic drug methotrexate (16) is shown in Fig. 2. The skeletal model of the active site residues—those containing atoms within 6 Å of any atom in methotrexate—is shown with red lines. The surfaces of atoms selected as both active site and surface atoms are represented as blue dots; the green lines and red dots represent the methotrexate molecule and its surface, respectively (17). To study this interaction in more detail, the conformation of either molecule and its surface can be varied interactively in real time, and global transformations such as scaling, rotation, translation, and sectioning may be performed to optimize the view. The speed of determining such a binding site, the generation and display of its surface and the surface of its substrate, and the ability to change the conformation of both molecules in real time are significant advantages in drug design. With the methods described in this report, it is possible to examine the steric interaction of many drugs with their receptors efficiently and rapidly. The resultant images are also very beautiful.

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11. This surface generator is now one of the commands (VDW) in MIDAS (Molecular Interactive Display and Simulation), a program for the display and manipulation of molecular models developed by C. Huang, T. E. Ferrin, L. Gallo, and R. Langridge at the Computer Graphics Laboratory, University of California, San Francisco, and used in all the work reported here. All programs were written in C and run with the UNIX time-sharing system (*12*) on a DEC VAX 11/750 by using an Evans & Sutherland Color Picture System 2. The software also runs on a VAX 11/780 under VMS with an Evans & Sutherland Color MultiPicture System, and similar software is under development for an Evans & Sutherland Color Picture System 300.
12. D. M. Ritchie and K. Thompson, *Commun. ACM* **17**, 7 (1974). UNIX is a registered trademark of Bell Laboratories.
13. The algorithm takes 0.03 central processing unit (CPU) seconds per atom at a density of five dots per square angstrom. Generation time is proportional to dot density. The algorithms of Connolly (*9*) and Pearl and Honegger (*10*) require 5 and 0.18 CPU seconds per atom, respectively, on comparable computers.
14. Interior atom removal takes 0.02 CPU seconds per atom.
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17. The entire process of site selection, surface atom selection, and surface generation for dihydrofolate reductase took 30 CPU seconds, and the surface generation of methotrexate took less than 2 CPU seconds.
18. We thank K. Davies, I. D. Kuntz, J. McClarin, and S. J. Oatley for discussions. Supported by NIH grant RR-1081 (R.L.), NIH graduate training grant GM 07379 (P.A.B.), and the University of California. P.A.B. is a graduate student in the Biophysics Graduate Group at the University of California, Berkeley.

6 May 1983; revised 29 June 1983

Mr. **Brown**. Can we go ahead with you, Dr. Vanden Bout?

STATEMENT OF DR. PAUL A. VANDEN BOUT, DIRECTOR, NATIONAL RADIO ASTRONOMY OBSERVATORY, CHARLOTTESVILLE, VA

Dr. **Vanden Bout**. Mr. Chairman, members of the task force, thank you for the opportunity to participate in this hearing.

What I would like to focus on in these remarks is how computers have impacted astronomy in the area of digital images and imaging processing, because I believe it is in that area that the most fundamental changes have occurred in the way that astronomers do their work. I will do this from the perspective of a radio astronomer.

Astronomers have always studied the universe by way of pictures, or as they are now known, images. For centuries those were formed in the eyes of people that looked up at the night sky. Following Galileo, they had telescopes to aid their views, but the images were still recorded as visual impressions of the observer.

Photography produced a revolution in astronomy because the photographic plate was much more sensitive than the human eye, and it also easily recorded an impartial view that contained an enormous amount of information.

Computers are affecting that same sort of revolution today, although in different ways. Modern astronomers use cameras at all wavelengths from gamma rays to x rays, ultraviolet, visible light, infrared, and radio wavelengths, and those cameras are the electronic equivalent of the photographic camera we are used to for visible light purposes.

The cameras are very different in different wavelength regions. They have one thing in common. They all produce digital images, that is, the picture consists of a set of numbers, one for each location in the picture that specifies how bright the photograph or image in at that point.

There are two characteristics of astronomical images that are very important. One is sensitivity; the other is resolution. Sensitivity refers to the amount of light necessary to record the image. You are looking at a golf ball on a distant green. How much light do you need to see it? Sunlight, at dusk, moonlight?

Resolution refers to the fineness of detail in the image. Two golf balls are on a green. You look at it. How far off can you be back and still recognize them as two objects instead of one?

Now, with respect to this latter characteristic, radio astronomers have been at a serious disadvantage with respect to their counterparts in other wavelength regions. They have had to learn to live with a fundamental law of physics, and in working with it, and around it, they have pioneered the use of computers in making images.

The physics that they have to battle is the fraction, which says that the resolution of a telescope is given by the wavelength at which it is used divided by the diameter of the telescope. Radio wavelengths are about a million times the size of optical visible light wavelengths, and that means that radio astronomers would have to construct telescopes a million times bigger than ordinary optical telescopes if they were to achieve the same resolution. Instead of building antennas of immense size, what radio astronomers have done is build arrays of antennas, and the first slide shows an array, a sketch of an array.

$$\text{Angular Resolution} \sim \frac{\text{(wavelength)}}{\text{(diameter)}}$$

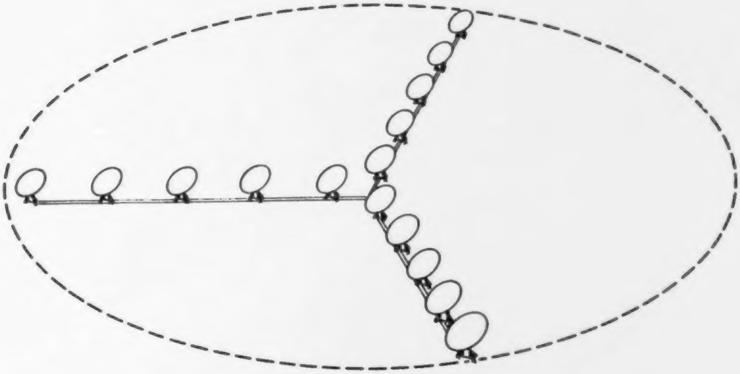

Figure 1. A fifteen-element array of radio telescopes with resolution roughly twenty times that of an individual antenna in the array.

This array has a resolution 20 times as good as that of a single antenna in the array because the resolution of an array depends on the distances between the telescopes, not on the diameter of a single telescope. It is as though one huge telescope had been synthesized by the use of a number of smaller telescopes.

A number of array telescopes like this exist in the world. The most powerful is the very large array which is located near Socorro, NM, and operated by the National Radio Astronomy Observatory.

It might help if we could dim the lights a little bit.

This array contains 27 antennas and in its fullest extent, it occupies an area comparable to that of the Washington, DC metropolitan area. It has a diameter of about 40 kilometers. To fill that area with individual antennas would take 2½ million antennas. Instead, 27 are used to synthesize such a telescope.

To control simultaneously all of those telescopes obviously takes computers. It is impossible to run such an instrument without computers. In some sense, the instrument has become a computer, but it also makes images digitally by the use of computers.

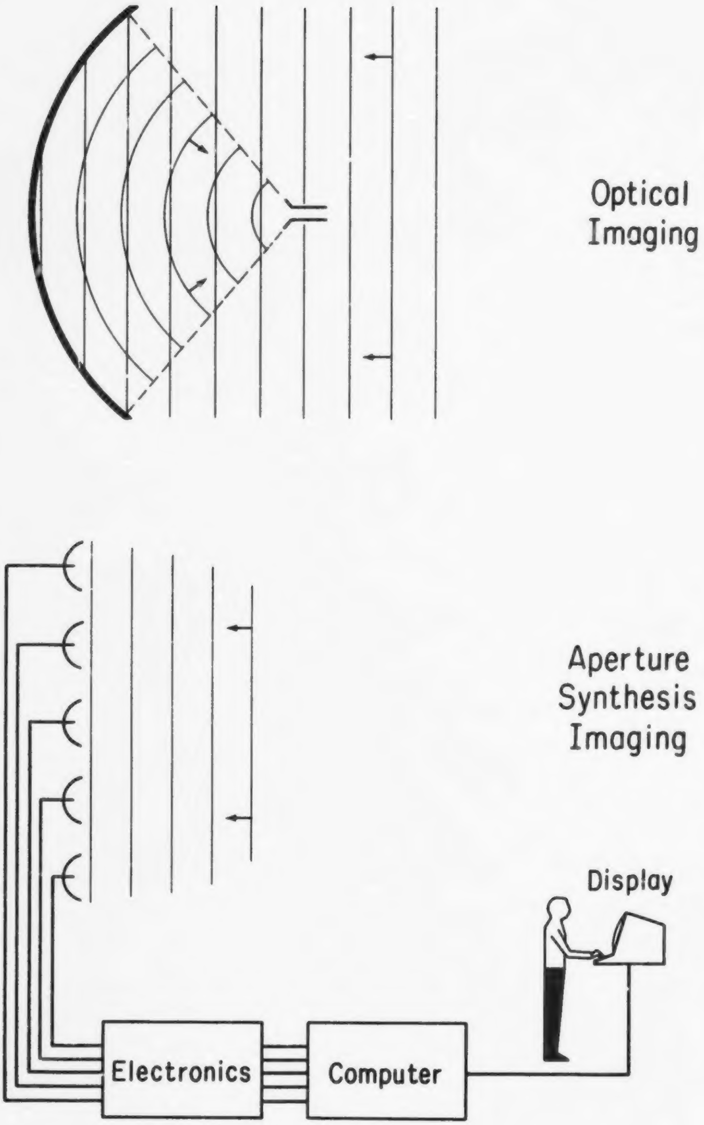
Optical
Imaging
Aperture
Synthesis
Imaging
Display
Electronics
Computer

Figure 2. The optical imaging by a single reflecting surface contrasted with aperture synthesis imaging where the "optics" consist of a computer.

At the top, you see normal traditional optical imaging. As the wavelength from the source falls on a curved surface, which reshapes it and directs it to a point, at the focus of that point an image is formed. In the array telescope, the wavelength is instead sampled by a large number of telescopes, and in the case of ELA-27, those signals from the antennas are compared electronically and then a computer transforms the image, transforms the data, into an image and makes the picture. So the optics of an array telescope is the computer. The flexibility that affords is the source of all of the power in digital images and image processing for the radio astronomer.

This is the data recorded by the VLA of a source. It is the equivalent of an optical hologram. If you look at it, you don't recognize any particular information about it. It requires transformation in a computer to turn it into the image which you see here.

This image is of the center of our own galaxy, the milky way. The bright red spot is the source Sagittarius A that Carl Jansky discovered in 1932 when radio astronomy began.

These are slides which show different ways of presenting the images. At the top is a radio photograph, how this source would appear in radio waves, but presented in a standard way as though you had taken a picture of the invisible light. Then, underneath there are contour plots of two different sorts. The radio astronomers now spend a great deal of time generating these sorts of graphical displays trying to get every possible view of the objects they are studying and to try to understand what is happening in these sources.

In addition to producing digital images by using array telescopes, computer controlled, it is possible to take digital images and process them. These images all contain noise. The noise has a number of origins, but the chief two sources of noise are instrumental, due to the fact that the array is not filled with telescopes, but there are only 27 rather thinly distributed throughout the array, and the other source of the noise is the atmosphere.

Now, on the top, you see a raw image of the radio source Cygnus A, a powerful radio source, and that image contains a great deal of detail in it which is entirely spurious. It is due to the fact that the sampling of the wave was incomplete, as I have said, and the atmosphere is disturbed way before it was sampled by the antenna.

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ACKNOWLEDGMENT: *Acknowledgment must be given to Observer(s) as listed below.*

DESCRIPTION: CYGNUS A (3C 405).

Extragalactic: High Luminosity Radio Galaxy.

These three images of the prominent radio galaxy Cygnus A represent different stages in modern processing of radio-interferometric data. See attached for detailed description.

Technical Data: Observing runs - 1982 → 1984 at the Very Large Array (VLA) radio telescope, 52 miles west of Socorro, New Mexico USA. Because of the range and complexity of structure, all VLA configurations were used with the full 27-antenna array. Wavelength - 6 cm. Frequency - 4885 MHz. Resolution - 0.35 x 0.35 arcsec. Field of view - 2 x 1 arcmin. Positive black-and-white image.

Right Ascension (1950): $19^h57^m44\overset{s}{.}44$
Declination (1950): $+40°35'46''\!.3$

Observers: Richard A. Perley
John W. Dreher

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The middle image has had all the instrumental effects removed. That can be done using powerful computer algorithms which have been developed rather recently.

The bottom image, in addition, has had all of the atmospheric disturbances and the improvement in quality from top to bottom is roughly a factor of 300 in so-called dynamic range; that is, the ratio of the brightest spot in the photograph or image to the noise that is in the background has increased by a factor of 100 in going through the image process. The price of doing that, of achieving this credible improvement in the quality of the images produced by the instrument, the price is a lot of computing.

Now, to what end? The question for the scientist in thinking about science policy is usually a simple one: What is there for me in this? What can I learn if I have a computer, for example, that I couldn't learn if I didn't have a computer? What have we learned using a computer driven instrument like the VLA that we wouldn't know if we didn't have that? What have we learned by virtue of the image processing that we would never have learned?

Let's look at another view of Cygnus A. This is a color image. It is difficult to see in this image, but I think in the written testimony, you have a black and white photograph in which you can see it more easily.

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DESCRIPTION: CYGNUS A (3C 405).

Extragalactic: A Powerful, Extended Radio Galaxy.

A radio 'photograph' of the extraordinary radio galaxy Cygnus A. The image has been especially processed to bring out the fine details in the two "radio lobes." A giant elliptical galaxy (not visible in this *radio* picture) is centered at the small "dot" in the center of the image. It is believed that the energy that powers the source originates here. A thin "jet" can be traced from this central "engine" to the right and upward. Through this channel the power is conveyed out into the lobes. The "wispy" appearance of the lobes was unexpected and, as yet, remains unexplained.

Technical Data: Observing runs - 1979 → 1983 at the Very Large Array (VLA) radio telescope, 52 miles west of Socorro, New Mexico USA. Because of range and complexity of structure, all VLA configurations were used with the full 27-antenna array. Wavelength - 6 cm. Frequency - 5 GHz. Resolution - 0.4 x 0.4 arcsec. Field of view - 2 x ≈1 arcmin. Computer processing performed at Jet Propulsion Laboratory (JPL) in Pasadena, California USA. The transfer function is not linear and varies across image. Positive black-and-white image.

Right Ascension (1950): $19^{h}57^{m}44\overset{s}{.}44$
Declination (1950): $+40^{\circ}35'46\overset{\prime\prime}{.}3$

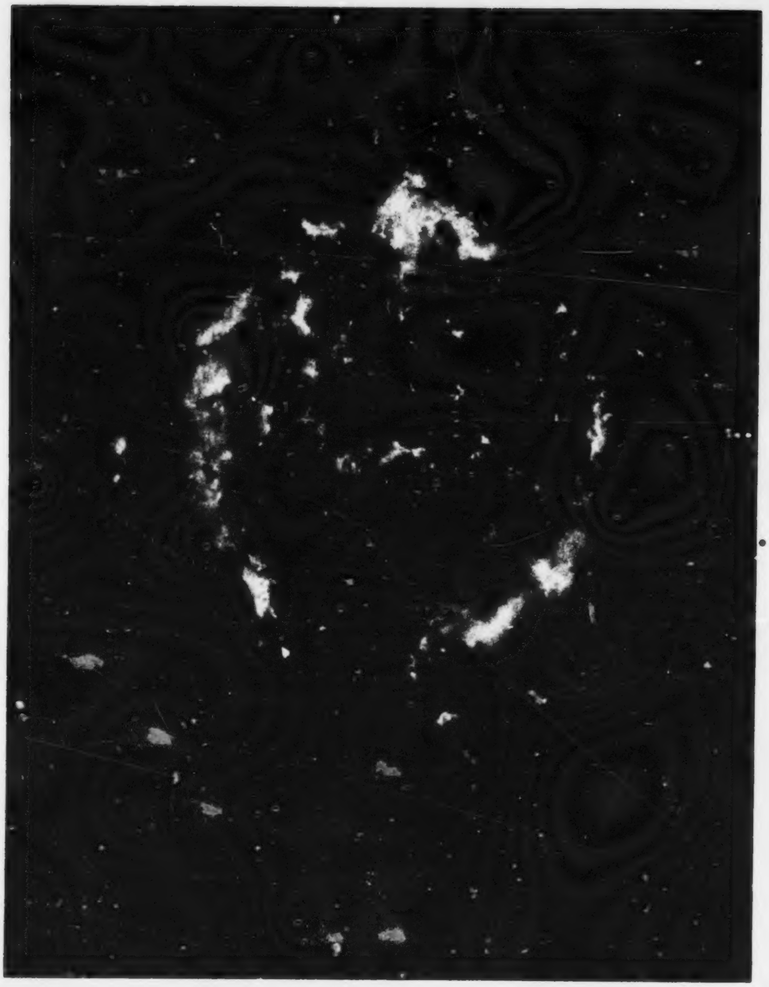
Observers: Richard A. Perley
John W. Dreher
John J. Cowan

Connecting the two radial lobes on either side, the bright sources of radio emission—connecting them with the dot in the center, which is a galaxy, you can see very thin streams of matter.

It was also speculated that the double lobe radio galaxies, which have been known for quite a while in astronomy, had to be driven by the central object in some way, but the direct evidence weighted for these digitally produced and processed images.

Now, you can actually see the connection between the galaxy in the center and the huge radial lobes on either side.

Here is another example. This image is the remnant of a cataclysmic explosion of a star. It occurred sometime hundreds of years ago in our own galaxy and with the VLA, plus incredible amounts of computing, in this case a supercomputer was required to produce this image, you can study for the first time in very great detail the interaction of this exploding fireball with the surrounding interstellar medium of the galaxy.



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DESCRIPTION: CASSIOPEIA A (Cas A; 3C 461).

Galactic: Supernova Remnant.

Cassiopeia A is the remnant of a catastrophic stellar explosion occurring approximately 300 years ago. This image depicts Cas A at C Band 1983.8 pixel size $0''.18 \times 0''.18$, 2048^2. Very Large Array (VLA) radio telescope A/B/C/D arrays at 5085, 4970, 4640, and 4410 MHz. Image deconvolved from 4096 x 4096 dirty map using maximum entropy method 'VM'. Twenty minutes of Cray CPU time required for deconvolution. The deconvolution reveals an artifact, seen in the form of rings emanating from the phase center, due to a single bad correlator in the A array North arm.

Technical Data: Observing runs - 1982 December + 1983 February + 1983 December/November at the Very Large Array (VLA) radio telescope, 52 miles west of Socorro, New Mexico USA. Wavelength - 6 cm. Resolution - 0.2 x 0.2 arcsec. Field of view - 6.1 x 6.1 arcmin. Mode of observation - continuum. Number of antennas - 27. Positive black-and-white image.

Right Ascension (1950): $23^h21^m13^s.00$
Declination (1950): $+58°32'35''.00$

Observers: Richard J. Tuffs
Richard A. Perley
Martin T. Brown
Stephen F. Gull

It is possible, in fact, to see changes. So data is being taken at yearly intervals, and at some time in the near future, I hope we will have a time lapse movie of this explosion.

This is another double lobe radio source, like Cygnus A, but in this case the lobes are faint enough so that you can see that they consist of a series of nebulocities on the right as though the galaxy sent out successive puffs of plasma to drive these radial lobes.

There is the new science that excites the radio astronomers when they think about computers in their world.

I think this is the last slide. It is intended to illustrate the following point. Not that long ago, a radio telescope consisted of a major mechanical structure with some very important electronics to receive signals and record them and possibly manufacture a computer nearby that would write the data down and make it convenient for analysis. The situation now is completely different. To the astronomer the system appears as a computer. He talks to the telescope through a terminal. He analyzes his data through a terminal. The whole system has become a computer with peripherals of the traditional sort, plus some telescopes or antennas as additional computer peripherals.

To summarize this, I would like, with your permission, to show a very short movie of 3-minutes length which will illustrate how the images that are digitally processed, improved step-by-step as the computer iterates toward the final image.

You can finally see the thin jets that connect the lobe with the central source, but only after the image has been processed in this way.

Mr. **Brown**. Since Mr. Lujan isn't here to defend New Mexico, I think I will have that whole operation moved over to California.

Dr. **Vanden Bout**. Thank you. That is it.

[The prepared statement of Dr. Vanden Bout follows:]

THE IMPACT OF THE INFORMATION AGE ON RADIO ASTRONOMY

Testimony Submitted to the
House Science and Technology Committee --
Subcommittee on Science Policy

Paul A. Vanden Bout
Director
National Radio Astronomy Observatory
Edgemont Road
Charlottesville, Virginia 22903

September 10, 1985

NATIONAL RADIO ASTRONOMY OBSERVATORY
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INTRODUCTION

The widespread availability of large and increasing amounts of computing capability has had an obvious impact on nearly every element of society, including science. That science should be affected by the so-called "information age" is hardly surprising. Science, broadly defined, is responsible for the existence of computers; scientists, as could be expected, have taken advantage of their invention.

How have computers impacted science? The Statement of Purpose for this Hearing divides this question into three areas: the conduct of research, the communication and use of the results of research, and the federal response to research policies and funding. This is a useful approach and I have attempted in this testimony to address the issues delineated by the Task Force in these areas. I want to point out at the beginning, however, that the following question, while contained in the whole of the concerns of the Task Force, is of overriding importance in the mind of the individual scientist--What can I learn with computers that I could not otherwise learn? Scientists are concerned with rapid communication of results, with more efficient and cost-effective modes of operating their facilities, better management of databases, and all the other issues computers have raised in science policy. But the driving force that shapes the decisions of scientists with respect to computers is the quest for new results.

The material which follows is divided into three areas, all involving radio astronomy--the field I know best and in which I have been active during the "computer revolution." The bulk of the discussion is devoted to digital imaging and image processing, for it is in these areas that computing has had the most profound impact on radio astronomy. That discussion includes remarks on automated control of telescopes and ancillary instrumentation. This is followed by a brief discussion of remote observing with the aid of computer networks. Finally, there is a discussion of data archiving and dissemination of databases. I have chosen to ignore the impact of computers on observatory management on the assumption that the impact in this area is no different than that familiar in business and industry.

DIGITAL IMAGING AND IMAGE PROCESSING

Digital imaging in Radio Astronomy

Astronomers study the universe by means of pictures, or to use a more modern term, images. Until Galileo the images were those formed in the unaided human eye. For centuries following Galileo's invention of the astronomical telescope, the images were recorded as the visual impressions of the astronomer. The invention of the photographic plate began a new era in astronomical imaging during which large advances were made in the sensitivity and fineness of detail that could be recorded. Modern astronomers construct their images using the electronic equivalents of the photographic camera. These devices take very different forms depending on whether it is a gamma-ray, x-ray, ultraviolet, visible light, infrared, or radio image that is to be produced. The common element is that the images produced are all digital, that is, the image consists of a set of numbers which specify the brightness at each point in the image. Computers have had an enormous impact on the quality of these digital images, and this is especially true for radio astronomy where the effects of the earth's atmosphere are sufficiently benign and the wavelength of the radiation is sufficiently large to allow both the amplitude and the phase of the radio waves from the source to be measured relatively easily. Computers have made it possible for radio astronomers to exploit these advantages and obtain astronomical images of higher resolution than those obtained at any other wavelength.

The law of diffraction would appear to restrict radio images to very low resolution. The resolution of an image--a measure of the fineness of detail that can be discerned in the image--is given (in radians) by the wavelength at which the image is made divided by the diameter of the telescope used. Even the largest radio telescopes at their shortest operating wavelengths have resolutions no better than about 1 arcminute, the angle subtended by a football at 1 km distance, approximately the resolving power of the unaided human eye.

Radio images of much higher resolution are now routinely obtained by arrays of multiple antennas, a technique that depends critically on the use of computers. For such instruments, the resolution depends inversely on the separations of the antennas in the array, not on the diameter of the individual telescopes in the array. As can be seen from Figure 1, the gain

$$\text{Angular Resolution} \sim \frac{(\text{wavelength})}{(\text{diameter})}$$

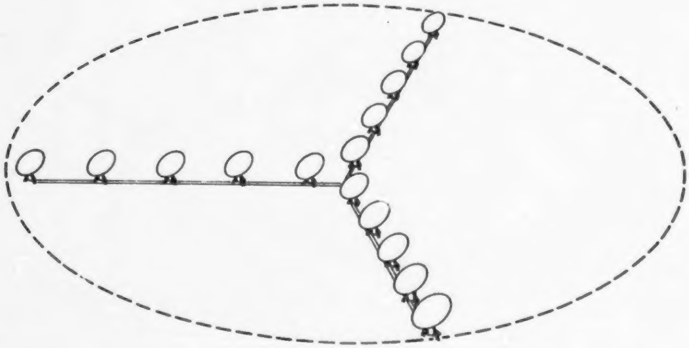

Figure 1. A fifteen-element array of radio telescopes with resolution roughly twenty times that of an individual antenna in the array.

in resolution can be substantial even for an array of modest dimensions. This technique was first demonstrated by Christiansen and Warburton /1 and Ryle /2 and later developed by M. Ryle at Cambridge, England. It is known as aperture synthesis imaging. It is worth noting that the development of aperture synthesis imaging was controlled by the availability of the first computers. Christiansen did not follow up his early work because the hand calculations of the Fourier Transforms were too laborious. In Cambridge computers had been introduced by the crystalographers, and Ryle's group took advantage of this.

The role of computers in aperture synthesis imaging is central to the way the image is formed. In ordinary optical imaging it is the reflecting surface itself that forms the image, reshaping the incoming wavefront from the source to a converging wavefront that forms an image of the source at the focus. This is shown in the top diagram of Figure 2. The bottom diagram of Figure 2 shows the process for aperture synthesis imaging. The incoming wavefront is sampled at discrete points across the array. Measures of the amplitudes of the correlations of the wavefront between these points are obtained, that is, the radio analogue of the hologram of the source is measured and then transformed into an image of the source by the computer. The "optics" of a radio synthesis array is a computer.

The importance of computing to aperture synthesis imaging can best be appreciated by considering a specific example. Of the several aperture

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/1. W. N. Christiansen and J. A. Warburton. "The Distribution of Radio Brightness Over the Solar Disk at a Wavelength of 21 cm, III. The Quiet Sun--Two Dimensional Observations," Australian J. Phys., vol. 135, pp. 151-174, 1955.

/2. M. Ryle, "The New Cambridge Radio Telescope," Nature, vol. 194, pp. 517-518, 1962.

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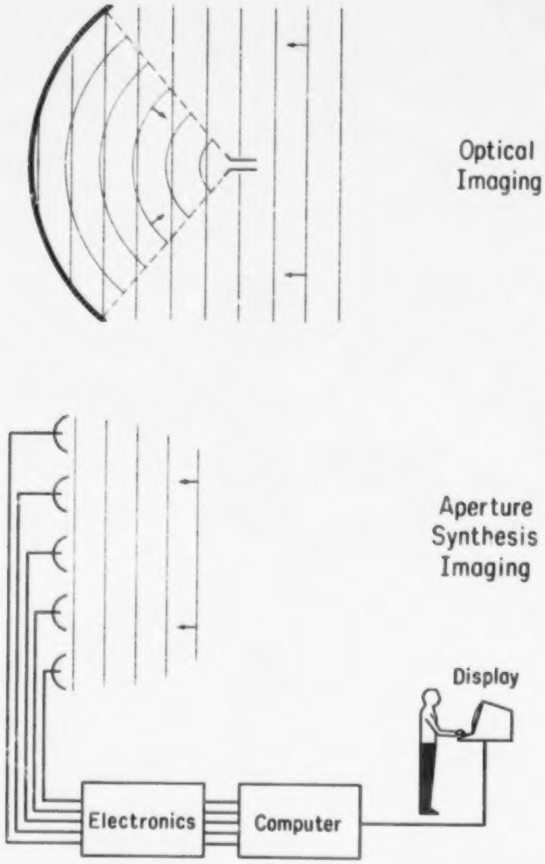
Optical
Imaging
Aperture
Synthesis
Imaging
Display
Electronics
Computer

Figure 2. The optical imaging by a single reflecting surface contrasted with aperture synthesis imaging where the "optics" consist of a computer.

synthesis arrays in the world, the Very Large Array (VLA) is the most powerful /3. The VLA consists of 27 antennas, each 25 m in diameter, in a wye configuration of maximum diameter 40 km. It operates at wavelengths from 1.3 to 21 cm with a resolution up to 0.05 arcseconds. This resolution is comparable to the best that can be obtained in visible light from the ground. Computers control the simultaneous movement of all the telescopes, the electronics that record and correlate the signals, and the monitoring system that keeps track of the state of numerous pieces of equipment located at each telescope, often miles from the central laboratory. The operation of the VLA is inconceivable without computers.

The problem of automated control and operation pales, however, compared with that of image production. In a typical observation the VLA produces 200,000 bits of information every 10 seconds. This amounts to nearly 100 billion bits per year, roughly the number required to specify the contents of a library of 10,000 books. These data must be calibrated and transformed into images. The images have from 128 to 4096 pixels or resolution elements on a side, containing from 1/4 million to 1/4 billion bits of information. An astronomer's observing run may produce anywhere from one to hundreds of these images.

Indeed, the VLA appears to an observer as something totally different from the traditional radio telescope. The contrast is illustrated in

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/3. The VLA is one of the observing facilities of the National Radio Astronomy Observatory, itself operated by Associated Universities, Inc., under contract from the National Science Foundation. The VLA is located on the Plains of San Agustín, 50 miles west of Socorro, New Mexico. A description of this facility is given by P. J. Napier, A. R. Thompson, and R. D. Ekers, "The Very Large Array: Design and Performance of a Modern Synthesis Radio Telescope," Proceedings of the IEEE, vol. 71, pp. 1295-1320, 1983.

Figure 3. Only recently a radio telescope was principally a large mechanical structure, with important electronics for control and signal detection, and, perhaps, a computer added for convenience in data recording and analysis. A modern aperture synthesis telescope, on the other hand, appears as a large computer or set of computers which include antennas and electronics as part of their peripheral equipment. The instrument is only approached, controlled, and used through computer terminals. The way a radio astronomer takes data has been changed by computers in an absolutely fundamental way.

Image Processing in Radio Astronomy

The resolution afforded by aperture synthesis arrays is obtained at a price. Because the wavefront is only sampled at discrete points, the resulting images are degraded from what would be produced if the array were completely filled with antennas. The array probes the sky with a beam that has "sidelobes," in the jargon of the trade. These degraded images are called "dirty images." Fortunately, powerful computing algorithms /4 exist which can remove the effect of the sidelobes to yield "clean images." The most commonly used such algorithm is, in fact, called CLEAN.

The algorithms that remove the effects of incomplete data sampling have markedly enhanced the power of synthetic aperture arrays, but at a cost of intensive computing. For example, the powerful radio source Cygnus A has been observed with the VLA and the dirty image is the top one of the three

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/4. T. J. Pearsen and A. C. S. Readhead, "Image Formation by Self-Calibration in Radio Astronomy," Annual Review of Astronomy and Astrophysics, vol. 22, pp. 97-130, 1984.

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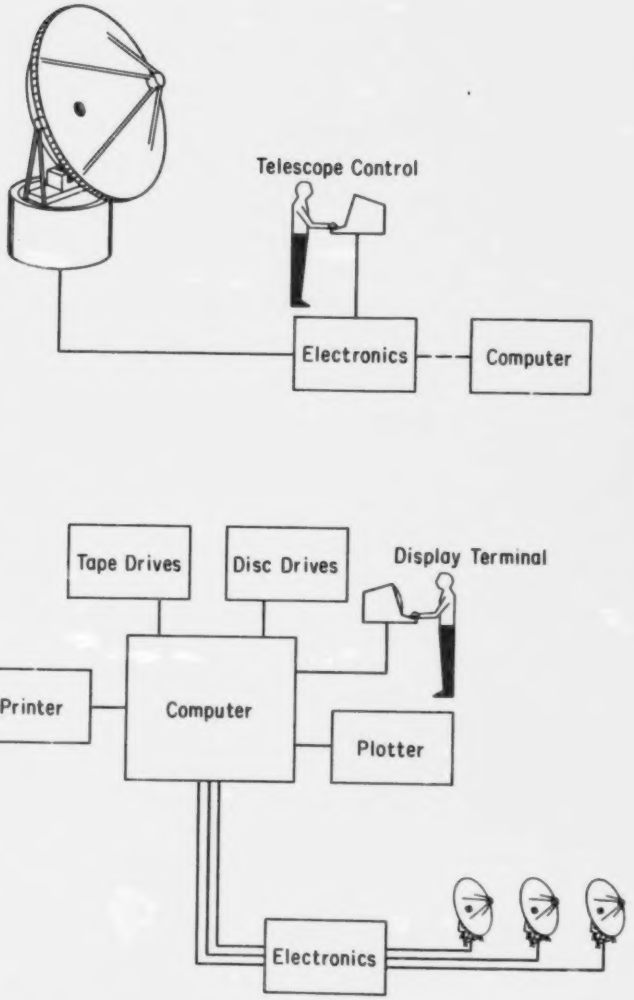
Telescope Control
Electronics
Computer
Tape Drives
Disc Drives
Display Terminal
Printer
Computer
Plotter
Electronics

Figure 3. Contrast between role of computers in a traditional (pre-1970) radio telescope and a modern aperture synthesis array.

shown in Figure 4. The middle image is the result of "cleaning" the dirty image. (In this particular case, a maximum entropy algorithm was used instead of the program CLEAN.) An obvious improvement in the image has been made. The improvement can be quantified by calculating the "dynamic range" of the images, that is, the ratio of the maximum intensity in the image to the mean noise level. For the dirty image, the dynamic range is about 100. The clean image has a dynamic range of about 10,000--a 100 times improvement.

Another limitation to the quality of aperture synthesis images is imposed by the earth's atmosphere. Irregularities in the atmosphere smaller than the array distort the wavefront before it is sampled by the array. the irregularities change in time; this is the radio analogue of the "twinkling" of stars. Because the VLA takes a large number of samples (correlations between all pairs of antennas) compared with the number of antennas, it is actually possible to calculate the atmosphere-induced errors and remove them from the data. This technique is called "self-calibration" or "hybrid mapping," and is the exact analogue of the use of deformable mirrors in adaptive optics to remove atmospheric "seeing" errors at visible light wavelengths. It is even more computing-intensive than CLEAN, but the results are worth the effort. The bottom image in Figure 4 has been self-calibrated. Improvements in dynamic range by a factor of 10 are typical of self-calibration. Figure 5 is a larger print of a Cygnus A image.

The magnitude of the additional computing effort required for image processing is overall about ten times that needed to calibrate and produce a dirty image. That factor is highly dependent on particular details,

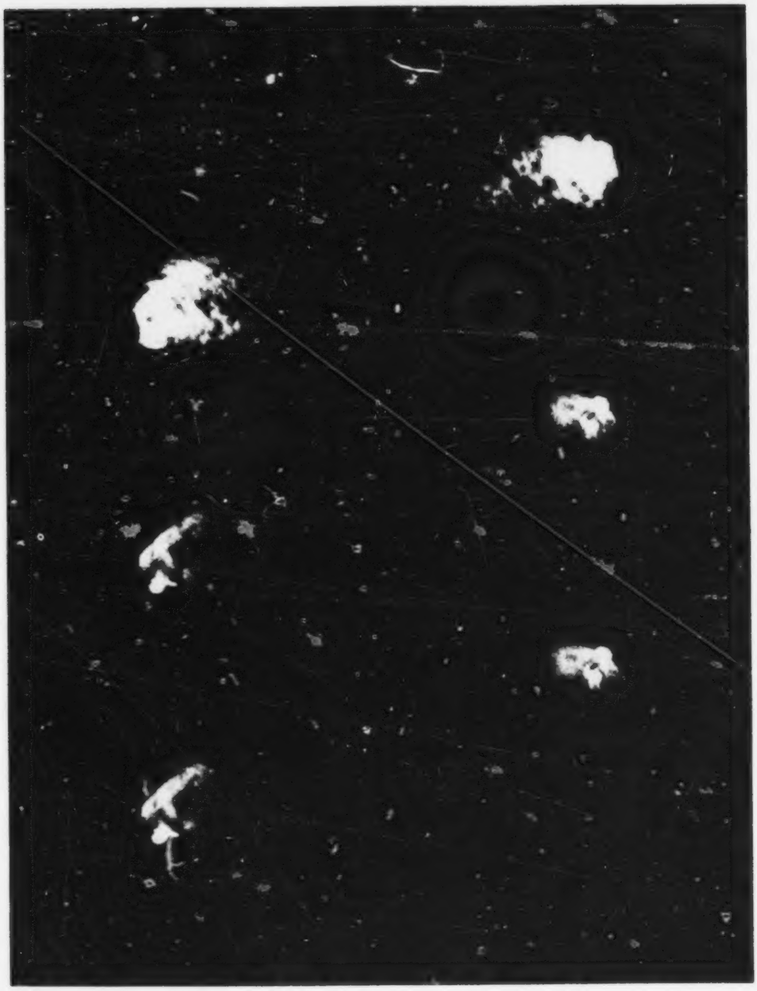

Figure 4. A series of three images of the radio source Cygnus A: the raw image (top); the image after instrumental noise, due to incomplete wavefront sampling, has been removed (middle); the image after atmospheric noise has been removed (bottom).

NATIONAL RADIO ASTRONOMY OBSERVATORY
EDGEMONT ROAD CHARLOTTESVILLE, VIRGINIA 22903-2475 USA
TELEPHONE 804-296-0211, EXT. 345 TWX 910-997-0174

NRAO FILE NUMBER: CV 84-CYGA.VRSp01D.

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CREDIT LINE: *The National Radio Astronomy Observatory, operated by Associated Universities, Inc. under contract with the National Science Foundation*

ACKNOWLEDGMENT: *Acknowledgment must be given to Observer(s) as listed below.*

DESCRIPTION: CYGNUS A (3C 405).

Extragalactic: High Luminosity Radio Galaxy.

These three images of the prominent radio galaxy Cygnus A represent different stages in modern processing of radio-interferometric data. See attached for detailed description.

Technical Data: Observing runs - 1982 → 1984 at the Very Large Array (VLA) radio telescope, 52 miles west of Socorro, New Mexico USA. Because of the range and complexity of structure, all VLA configurations were used with the full 27-antenna array. Wavelength - 6 cm. Frequency - 4885 MHz. Resolution - 0.35 x 0.35 arcsec. Field of view - 2 x 1 arcmin. Positive black-and-white image.

Right Ascension (1950): $19^{h}57^{m}44^{s}.44$
Declination (1950): $+40°35'46''.3$

Observers: Richard A. Perley
John W. Dreher

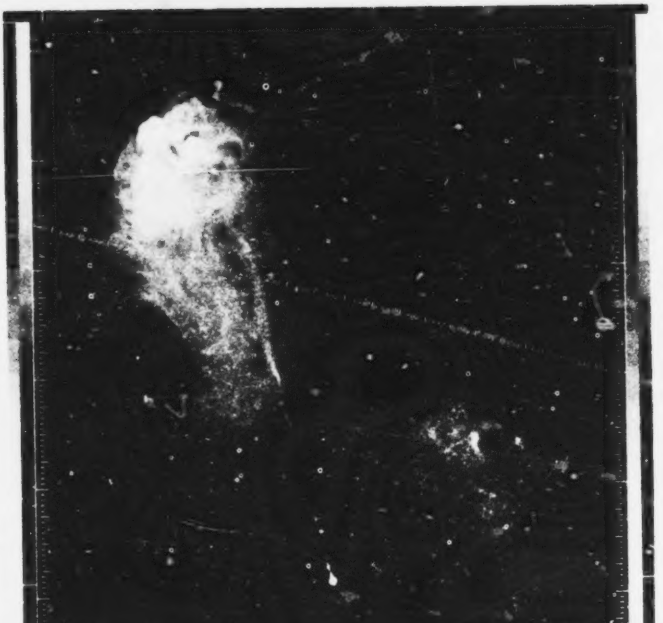

Figure 5. An image of the radio source Cygnus A which shows the tenuous streams of matter connecting the radio lobes to the central galaxy.

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TELEPHONE 804-296-0211, EXT. 345 TWX 910-997-0174

NRAO FILE NUMBER: CV 83-CYGA.VR10.1A.

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ACKNOWLEDGMENT: *Acknowledgment must be given to Observer(s) as listed below.*

DESCRIPTION: CYGNUS A (3C 405).

Extragalactic: A Powerful, Extended Radio Galaxy.

A radio 'photograph' of the extraordinary radio galaxy Cygnus A. The image has been especially processed to bring out the fine details in the two "radio lobes." A giant elliptical galaxy (not visible in this *radio* picture) is centered at the small "dot" in the center of the image. It is believed that the energy that powers the source originates here. A thin "jet" can be traced from this central "engine" to the right and upward. Through this channel the power is conveyed out into the lobes. The "wispy" appearance of the lobes was unexpected and, as yet, remains unexplained.

Technical Data: Observing runs - 1979 → 1983 at the Very Large Array (VLA) radio telescope, 52 miles west of Socorro, New Mexico USA. Because of range and complexity of structure, all VLA configurations were used with the full 27-antenna array. Wavelength - 6 cm. Frequency - 5 GHz. Resolution - 0.4 x 0.4 arcsec. Field of view - 2 x ≈1 arcmin. Computer processing performed at Jet Propulsion Laboratory (JPL) in Pasadena, California USA. The transfer function is not linear and varies across image. Positive black-and-white image.

Right Ascension (1950): $19^{h}57^{m}44^{s}.44$
Declination (1950): $+40°35'46''.3$

Observers: Richard A. Perley
John W. Dreher
John J. Cowan

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however, and the example given here of the Cvgnus A image required more like 100 times as much computing as the dirty image, a factor typical of the most demanding and scientifically interesting cases.

A second example of state-of-the-art radio image processing is shown in Figure 6. This image is of the supernova remnant Cassiopeia A. It could only be produced using a so-called supercomputer due to the size of its database. The map contains 16 million pixels. It was made from data taken with all four standard configurations of the VLA; the raw data fill 20 reels of 1600 bpi, 2400 ft magnetic tape. The supercomputer time was obtained through the NSF Office of Advanced Scientific Computing. Twenty minutes of cpu time were required.

What is the new science made possible by computer-intensive image processing? The Cygnus A image illustrates one important result. For years astronomers have been aware of radio galaxies, which often came in the form of two radio-emitting lobes, such as seen here, equi-distant from a central galaxy that can be seen in visible light. It was speculated that the lobes were either ejected by the central object or powered by it in some way. The image in Figure 4 reveals the tenuous thread of matter that connects the galaxy to the lobes--but this is seen only in the image that has been cleaned and self-calibrated. Scientifically, such an image is priceless since it unequivocally demonstrates the role that the central galaxy plays in continuously fueling the radio lobes. The extraordinary energy flowing from the galactic center leads to the critical inference that a black hole exists in the center of this particular radio galaxy. Without powerful image-processing algorithms and high-speed computers the nature of these sources would have been left in the realm of speculation.

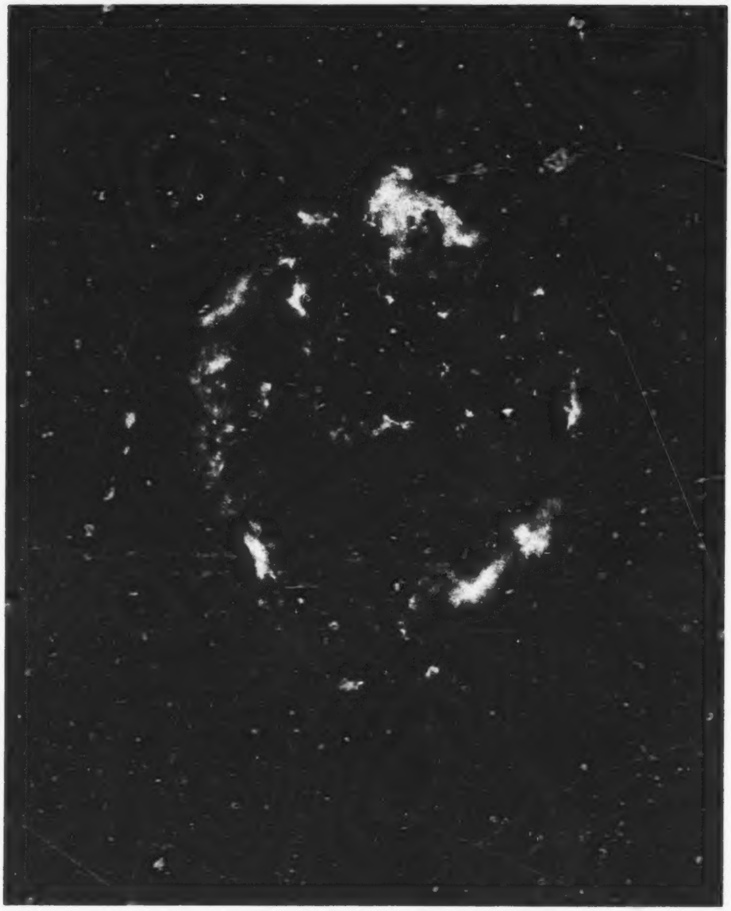

Figure 6. An image of the supernova remnant Cas A. This large image has 4096x4096 ≈ 16 million resolution elements ("pixels") and required the use of a supercomputer for its production.

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EDGEMONT ROAD CHARLOTTESVILLE, VIRGINIA 22903-2475 USA
TELEPHONE 804-296-0211, EXT. 345 TWX 910-997-0174

NRAO FILE NUMBER: CV 83-CASA.VRO9R.

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CREDIT LINE: *The National Radio Astronomy Observatory, operated by Associated Universities, Inc. under contract with the National Science Foundation*

ACKNOWLEDGMENT: *Acknowledgment must be given to Observer(s) as listed below.*

DESCRIPTION: CASSIOPEIA A (Cas A; 3C 461).

Galactic: Supernova Remnant.

Cassiopeia A is the remnant of a catastrophic stellar explosion occurring approximately 300 years ago. This image depicts Cas A at C Band 1983.8 pixel size 0".18 x 0".18, 2048^2. Very Large Array (VLA) radio telescope A/B/C/D arrays at 5085, 4970, 4640, and 4410 MHz. Image deconvolved from 4096 x 4096 dirty map using maximum entropy method 'VM'. Twenty minutes of Cray CPU time required for deconvolution. The deconvolution reveals an artifact, seen in the form of rings emanating from the phase center, due to a single bad correlator in the A array North arm.

Technical Data: Observing runs - 1982 December + 1983 February + 1983 December/November at the Very Large Array (VLA) radio telescope, 52 miles west of Socorro, New Mexico USA. Wavelength - 6 cm. Resolution - 0.2 x 0.2 arcsec. Field of view - 6.1 x 6.1 arcmin. Mode of observation - continuum. Number of antennas - 27. Positive black-and-white image.

Right Ascension (1950): $23^h21^m13^s.00$
Declination (1950): +58°32'35".00

Observers: Richard J. Tuffs
Richard A. Perley
Martin T. Brown
Stephen F. Gull

The Cassiopeia A image provides another example of new scientific results. The fine structure in the image makes it possible to study in detail the interaction of an expanding supernova shell with the surrounding interstellar medium, particularly so if a time sequence of such images is obtained. Changes in the structure on time scales as short as one year could be measured.

Image Processing Software

As might be surmised from the discussion thus far, the production and maintenance of image processing software is a major activity at an observatory with an aperture synthesis telescope. Image processing software is an important element in all of astronomy for that matter. Given the diversity of the field, there has been astonishingly little duplication of effort. In optical astronomy there has been an evolution from IPS (Image Processing System), the first major system for astronomy in the U.S., to IRAF (Image Reduction and Analysis Facility), which is to be used at the National Optical Astronomy Observatory and the Space Telescope Science Institute. In radio astronomy the image processing system used by nearly all observers is AIPS (Astronomical Image Processing System) /5. AIPS is a world standard for radio observers although complementary systems exist, for example, GIPSY developed by Kapteyn Astronomical Institute in Groningen, The Netherlands, for the specialized needs of users of the Westerbork Synthesis Radio Telescope, and STARLINK, a network of VAX computers and image processing software used in England. Numerous small, special systems exist

/5. AIPS is described in two NRAO internal publications: The "AIPS Cookbook," a user's manual, and "Going AIPS," a two-volume programmers manual. Both are available from the Computer division, NRAO, Charlottesville, VA.

at universities, largely for the reduction of optical data. The major systems developed at the Jet Propulsion laboratory for the processing of spacecraft TV images must also be mentioned.

The image processing systems are the result of major software efforts. AIPS has nearly one-half million lines of computer code. No individual astronomer can afford the time or resources to produce a software package of this magnitude. Such systems are of necessity developed and maintained at national facilities.

Virtually all university-based radio observers use AIPS because it was specifically designed to be easily portable to university computers. The AIPS group at the NRAO which developed the software is also responsible for maintaining it. Every three months a new version of AIPS, with additions to the system and corrections to problems in earlier versions, is shipped to approximately 60 image processing centers in the NRAO user community. An AIPS newsletter, sent to 400 addresses, keeps the users informed of changes.

By insisting on portability in designing the AIPS software, it has become possible to bring this system up on a variety of computers with relative ease. Thus, although AIPS is programmed and runs first on a VAX 11/780 under the VMS operating system, it now runs on VAX's with UNIX operating systems, ModComp, Harris, IBM, Charles River, and several other brands of computers, including most recently a Cray XM-P supercomputer and the Convex and Alliant brands of mini-supercomputers. Without this portability the power of the image processing algorithms would not have been nearly so available to the user community of the VLA.

Image processing systems require specialized hardware, as well as software, to display the images being processed, to store intermediate results, and to rapidly move data between the various subsystems of the computer being used. Of particular importance to radio astronomical image processing is the fact that the effects that degrade the images and are to be removed by the processing connect all the parts of the image. This means the speed of modern computers can only be realized if the entire image is resident in the memory of the computer so that no time need be spent moving data between memory and disk storage. That implies computers with massive memories are required--upwards of 16 megawords for the largest images that are presently constructed.

Finally, I want to point out that the advent of image processing is not unique to astronomy and that the efforts of astronomers to develop image processing systems has brought them into contact with these other fields. Indeed, some of the early work on image reconstruction in medical tomography was developed directly from the papers on radio imaging. A workshop on synthesis mapping held recently in Socorro, New Mexico, by the NRAO was attended by several representatives from other disciplines, including the entire research and development staff of an industrial concern building nuclear magnetic resonance imaging instruments for medical applications. Such mutually beneficial exchanges should be encouraged.

REMOTE OBSERVING

If a telescope is under the control of a computer, as most telescopes are today, the opportunity arises for remote observing, that is, use of the telescope by a user who does not come to the telescope but rather does the observing from a distance, communicating with the telescope and its instrumentation through computers linked by telephone lines. Remote observing appears to offer many advantages.

In some cases it is an absolute necessity. Spacecraft-based telescopes are an example. For telescopes at remote sites, difficult to reach and with possibly forbidding working environments, remote observing may be best. A recent advertisement of GTE describes how users of the United Kingdom Infrared Telescope on Mauna Kea, Hawaii, can do their observing from the Royal Observatory in Edinburgh, Scotland, using such a computer/satellite communications link. Academic deans would probably welcome any system that allowed their faculty to use telescopes without leaving campus and classes. Travel costs have long been an important element in astronomy research budgets. Could these be reduced with remote observing?

The experience at NRAO with remote observing lies in two areas--the VLA and data taken at the 140-foot telescope for Very Long Baseline Interferometry experiments involving several telescopes a widely different locations. The latter are totally automated and routine. No connection between telescope and observer is required at the time of the observation. Observations are planned, executed, and the data is assembled after the fact from all the telescopes involved for correlation and analysis.

The VLA procedure is similar for the programs it can handle remotely. An observer prepares the observing command file using a computer at the VLA site which is accessed by modem and telephone line from his home institution. The observations are made and the data are calibrated by VLA staff and sent to the observer. The observer reduces the data and produces images using AIPS on his university's computer. Roughly 20% of all VLA users choose to observe this way. An additional 20% of the users will prepare their observing files remotely, have the data taken, and visit the VLA site when convenient to calibrate the data and process images. Overall, the travel savings are almost exactly offset by the additional personnel required. The convenience to the user is significant, however.

If remote observing were to become the preferred mode for all users, the VLA would suffer. The most creative use of the instrument and the stimulus for its further development come from the interchange of ideas between users and staff that occurs informally in the course of visits by users to the VLA site. Those interactions must be preserved in planning for future VLA operations. The same is true of all astronomical observatories.

Similarly, if astronomical observing becomes a purely remote procedure so that the observer sees no more than a computer terminal, the training of students will suffer. Concerns have been expressed over the fact that students are increasingly using astronomical instruments as "black boxes," and not acquiring skills in instrumentation because those are gained only by "hands on" experience with the hardware. Remote observing exacerbates this problem and other steps must be taken to give students involvement in instrumentation development if remote observing becomes more common.

DATA ARCHIVING AND DISSEMINATION

Astronomers have always tended to archive their hard-won data. Perhaps the most famous traditional data archive is the Harvard Plate Collection, a set of photographs of the northern sky as periodically recorded over many years. A recent example of the usefulness of even old and incomplete data sets was presented at the last meeting of the American Astronomical Society where G. de Vaucouleurs discussed his analysis of the observations of the supernova S Andromeda which occurred in 1885. Despite obvious benefits, data archiving was difficult even with the low-cost efficient medium of the photographic plate. Modern computers have not only changed the nature of the data to be archived but have also made it possible to acquire much more data requiring archiving; computers have made the problem worse.

The VLA records 100 billion bits per year, roughly 2000 magnetic tapes. A long list of other databases could be given for ground and space-based observatories, all of which have archived their data or intend to do so when they begin operations. For the present, the storage of magnetic tape is not an overwhelming problem for the VLA, but in time we will have to switch to laser disk storage. Optical storage media will also be necessary for future major space observatories.

The storage of data is, in my opinion, a relatively easily solved technological problem for astronomy provided the laser disk storage technology keeps developing. The organization and sharing of these databases, on the other hand, could easily prove to be more difficult. It is not that the data are all written in different formats. In fact, the vast majority of astronomical data that is being archived is in the same format, so-called FITS (Flexible Image Transport System) format /6.

The FITS format was developed following a meeting in 1979 hosted by the NSF Astronomical Sciences Division where representatives of the national

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/6. D. C. Wells, E. W. Greisen, and R. H. Harten, "FITS: A Flexible Image Transport System," Astronomy and Astrophysics Supplement Series, vol. 44, pp. 363-370, 1981. E. W. Greisen and R. H. Harten, "An Extension of FITS for Groups of Small Arrays of Data," op. cit., pp. 371-374.

astronomical facilities discussed the problem of image data sharing. FITS has been adopted as the standard by nearly every major observatory in the world and has been endorsed by nearly every professional society in the astronomical community, including the International Astronomical Union.

The problem with image sharing is likely to be one of access to the database and possession of the means to work with the database, that is, access to an image processing system suitable for the job. In the case of VLA data, the NRAO will make data taken by an astronomer publicly available 18 months after the observations were made. Following recalibration by NRAO staff, anyone requesting the data can then reduce it using AIPS. NASA has similar rules for public access to data taken with space observatories. Data transport is accomplished by shipping magnetic tape. An experienced user of a facility, with adequate facilities at his home institution, will probably be able to make good use of such data; a novice will be at sea with it.

Finally, it should be pointed out that numerous catalogs and surveys of the sky in various wavelength regions have been made and are now commonly distributed in the form of magnetic tape. These surveys/catalog data comprise the fundamental reference material for astronomical research; a researcher lacking computer access to this material is at a severe disadvantage.

CLOSING REMARKS

There has been considerable discussion for the past several years among those concerned with science policy over the funding available for capital equipment in the nation's research laboratories, particularly at universities. The point I want to make is that this problem has been compounded, not eased, by the need for computing capability. In radio astronomy the focus may be shifting to computing, but the telescopes and receivers remain as essential as ever. Without them there is no data to process.

I want to applaud the programs underway to provide access to supercomputers for the U.S. scientific community. The access time provided by the NSF Office of Advanced Scientific Computing to the NRAO has provided some of the most interesting new developments in radio astronomical image processing; I predict that it will do the same for other fields, that is, supercomputing capability will do as much for researchers with the need to process large amounts of empirical data as it will for those concerned with theoretical calculations and modelling.

APPENDIX A

Two pages from the most recent issue of the NRAO Newsletter announcing a program of user participation in NRAO's test program of image processing on a supercomputer made available through the NSF Office of Advanced Scientific Computing.

A poster depicting astronomical computing being done on a Cray XM-P computer at Digital Productions, one of the supercomputer access facilities of the NSF Office of Advanced Scientific Computing.

PROCESSING WITH THE DIGITAL PRODUCTIONS CRAY

NRAO has been using the NSF Super Computer Access program to develop software for processing synthesis telescope images on a Cray XMP at Digital Productions, Los Angeles. This project is proceeding on schedule, and we are close to the stage where we need to do further testing with real data. At present we have working a stand-alone version of the VM deconvolution algorithm on images up to 4k x 4k (see Cas A result reported in this Newsletter) This program can be used when the appropriate dirty map and beam are available on a FITS tape. Processing is about 100 times faster than using AIPS on a VAX -11/780 + AP. Intermediate images can be dumped at each iteration. These have been used by Rots and Cornwell to make a movie, "Perfecting the Lens," illustrating the convergence of deconvolution algorithms.

Adapting the AIPS software package to the Digital Productions Cray is proceeding on schedule, and we are now close to the stage where AIPS can be used to make images (either using UVMAP or MX) from UVITS data. Preliminary timings indicate that the gains in speed over the VAX 11/780 + AP are less substantial than those achieved for the stand-alone VM. However, the array processor emulation Q-routines have not been optimized for the Cray so far, but will be soon.

This initial implementation is not highly interactive and image display functions are rudimentary. Furthermore, all processing done at this stage should be considered part of our software and operations test, i.e., we do not guarantee the results. Nevertheless, we believe the processing power and software already available can be used to produce new science and we should like to extend this test phase to include a range of projects from the user community.

To be suitable, projects should satisfy the following requirements:

1. The project should be sufficiently well defined to use the batch processing environment now available. Appropriate imaging and deconvolution parameters must be known in advance.

2. Since editing of bad data is not currently practical on the Cray, data integrity should be already established.

3. Processing of spectral line and snapshot observations yielding multiple images is encouraged since at this stage the Digital Productions Cray hardware is not well optimized for large (greater than 1k) images.

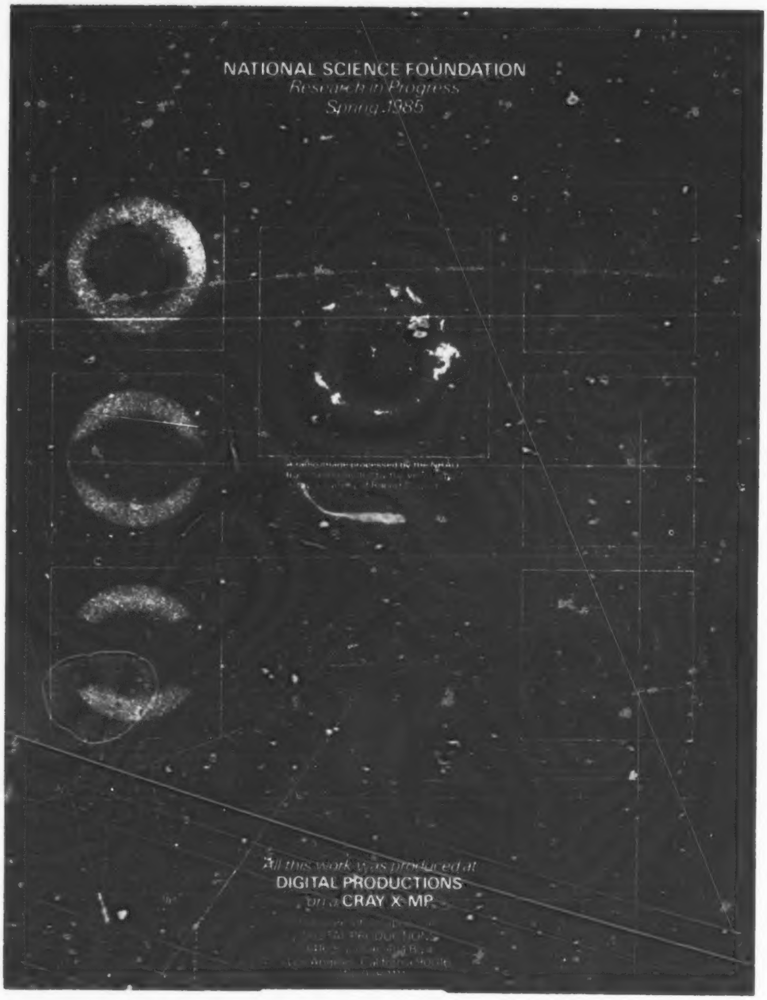
4. To use the stand-alone VM program, FITS tapes with dirty maps and beams must be available.

5. Processing times should be inconveniently (or impossibly) long on NRAO's VAX system.

Astronomers with existing data satisfying the above criteria who would like to take advantage of this program should write to me giving details of their requirements. Since the availability of the supercomputer resources at this time is primarily for test purposes, allocations will be based on technical suitability. If you have technical questions about this program, contact Tim Cornwell or Bob Duquet at the VLA or Kerry Hilldrup at Charlottesville.

By late 1985 and during 1986 we anticipate that we will be able to provide an operational processing capability on the Digital Productions Cray using an expanded NSF Access program. Further details will follow in future Newsletters.

R. D. Ekers



NATIONAL SCIENCE FOUNDATION

Research in Progress

Spring 1985

All this work was produced at

DIGITAL PRODUCTIONS

on a CRAY X-MP

APPENDIX B

A movie entitled "Perfecting the Lens." A copy of this movie has been given to the Task Force on Science Policy staff. An edited version was shown during the hearing on September 10, 1985. The movie was made by NRAO staff to illustrate the power of computer image processing algorithms for improving the quality of aperture synthesis radio astronomical images.

Mr. **Brown**. All right. I would like to go ahead then with Dr.—how do you pronouce your name?

Dr. **Armelagos**. Armelagos.

Mr. **Brown**. Armelagos.

I am positive that anthropologists can't use computers in any way.

STATEMENT OF DR. GEORGE J. ARMELAGOS, PROFESSOR OF ANTHROPOLOGY, UNIVERSITY OF MASSACHUSETTS, AMHERST, MA

Dr. **Armelagos**. Mr. Chairman, members of the committee, thank you for the opportunity to speak before your committee. Anthropology is a diverse discipline that bridges both the cultural and biological sciences. The cultural anthropologist is concerned with the adaptation of contemporary human populations.

In a sense, when we talk about adaption we are concerned with how populations are adjusting to their environments, and one of the important aspects of this adjustment is information transmission. It is sort of interesting to see that as anthropologists become aware of the information age, they start utilizing some of the buzz words that are part of the scientific community. Anthropologists have studied groups as diverse as the sand from the Kalahari Desert to street groups—street gangs in New York City.

Part of the aspects of anthropology is comparative studies using a cross-cultural perspective and another aspect of the research is field work. These remain key elements in the training and research of cultural anthropologists. Part of this research is an attempt to systematically research technology the way in which energy and information is extracted from the environment, to understand how this interacts with the social system, how people organize themselves in order to maintain and reproduce themselves and ideologies added to ideals, ideas and beliefs about the aspect of the environment, the supernatural and other parts of the cultural environment.

I should mention that in listening to some of the discussion early today, part of the problem that we have within the application of technology is this disparity between social systems and ideology, oftentimes a lag, and part of the problem that the first speaker talked about was the difficulty with having an ideology that will accept new technology in an efficient manner.

There are some other aspects of anthropology that are important such as linguistics which is the study of languages and anthropologists have specialized in the recording of languages that are unwritten, and they are able to deal now with these unwritten languages but broader problems that are also relevant to this new information age. For example, linguistic anthropologists are interested in the origin of language's relationship between biology, the brain, language, and culture, and the aspect of artificial intelligence is one area, for example, that we are concerned with in this area.

The third subdiscipline within anthropology is archeology which, again, is just cultural anthropologists which are concerned with the prehistoric adaptations of human populations. We have been around on this earth for 4 million years and cultural anthropologists have been able to document this existence. I, myself, am a biologist and anthropologist, and we are interested in understanding the extent of human variation as it exists in extant, in extinct populations.

In one other sense going back to the notion of an information age, we are interested in how genetic information, biological information is transmitted. So what is so ideal about the anthropological studies, one of our strengths is this ability to deal with information transmission in a nongenetic mode culture with information transmissions in the biological sense, genes and so forth.

It is probably one of our weaknesses, too. We try to spread ourselves too thin, and we have problems. Some of the common perspectives that we find within anthropology are the importance of culture, the system of energy transmission and energy extraction and the concept of adaptation.

We are also interested in the cross-cultural perspective and the aspect of being able to look at situations from time depth. Now why I think this is important is that we are living in an environment in which we have an extremely rapid change occurring within the environment, and it seems to me that anthropologists are in a situation to deal with this.

One of the, I think, interesting approaches that anthropologists should have is just with the new changes in computer technology and what implications does this have for the social system and for our ideological system.

I have three objectives today. I want to discuss a little bit about the role that computers play in modern anthropological research, and I will offer some suggestions to what changes and the impact the changes and new technology will have on anthropology and offer some suggestion which may allow for more effective uses of computers within anthropology.

In 1962, the Wenner-Gren Foundation, which is a very influential philanthropic organization, sponsored an international conference on the use of computers in anthropology. This was an attempt at providing not only the state-of-the-art of computers within anthropology but also concerned with discussing the potential use of these. What I found interesting is reading this report of the conference is that 23 years since this conference was held, I find that many of the issues and problems are still there. Anthropologists are still concerned with how you analyze textural material. They are also concerned with problems of what the impact of the computer was going to be on anthropology, and there were some anthropologists who were arguing that maybe we should not use computers. It is going to try to make us too scientific. I don't understand that reasoning, but that was something that was expressed.

There are a number of innovative suggestions on the use of computers that reflects, I think, the vision of these early pioneers, yet as you read many of the papers you are struck with the limited perspective that many of these early anthropologists showed.

Most of them saw the computer as a number cruncher to do statistical analysis and also was concerned with the descriptive classifications that were occurring. So they were concerned with racial analysis or typological analysis of artifacts and what they were concerned with is being able to do this in a very rapid fashion.

Now, in terms of the changes that computers will eventually have is, I think, moving us from beyond this descriptive stage into one where we are concerned with processes and mechanisms of change. The ability to analyze vast amounts of data is essentially a given within our understanding of the computer technology, but I think there is a more important aspect of the uses of computers by anthropologists which reflect a better understanding of their potential as a research tool.

The use of computers on anthropologists probably had its greatest impact on the subdisciplines of archeology and biological anthropology. Many of the technological developments in computer hardware and software had major impact in archeology in the storing, retrieval and manipulation of archeological data. Archeologists successfully use computer technology in analyzing artifacts and in incorporating technological advances that were based on computer technology.

Again, I think if you were to talk to many of the archeologists, they wouldn't realize that they were using computers because much of this is engrained within the technological hardware that they are using. Archeologists are able to use computers, in addition to the use of computer for manipulating large data sets in the descriptions of artifacts, some of the recent advances illustrate the potentials that computers have in analysis and interpretation of prehistoric remains.

Since the excavation or the digging of a site destroys it, the ability to retrieve information is fundamental to archeology and to archeological research. So it is not surprising that some of the earliest programs designed were to limit the distributions of artifacts in a site.

Can I just have the—I have got four slides I want to show rapidly here. This is from the crew before you which is the work of Glen Isaac and this shows a site in which bones from various animals, artifacts and plates are designed. What they are able to do with computer analysis is that they can call various materials at different times. So you could call, for example, all of the bone material or all of the stone material or the animal remains and in doing this what you can do then is make certain interpretation.

For example, at the site that this illustrated, that this was illustrated, was taken from, it was a hippopotamus kill site. Not only were they able to tell there was a hippopotamus there that was probably mired down in mud, they were able to actually interpret the way in which this animal was butchered.

Now, what is important in this aspect of this research is that what they are able to do then is to try to interpret behavior. Now, the reason that the computers had such an impact within the area of archeology is that archeology is essentially a labor intensive activity. Forty to 50 percent of the field work is involved in—40 to 50 percent of your time in the field is involved in field work—the excavations themselves—about 25 to 29 percent in post-field work analysis, analyzing the artifacts and 14 to 20 percent is involved in report writing. So obviously when you have labor intensive activities such as this the more time that the computer can save for you, the better off you are going to be.

Now, Sylvia Gaines, who is an archeologist at Arizona State University reports as early as 1971 they had the system ADAM, which is archeological data analysis and management system in the field. This represented hardware and which was a terminal to the main computer at Arizona State University and computer programs for the storage of data and for data retrieval and data manipulation. This allowed the archeologists immediate feedback on materials being excavated. So what happens then is that by utilizing the terminal and connecting it to the computer, which was 483 kilometers away, they were able actually to make and utilize this information in dealing with daily tactical decisions.

But this early use of computers had all kinds of difficulties. For example, there was poor telephone transmission and so the information was not being transmitted properly and she even tells the time that the operater would interrupt and want to know what all the beeps and buzzes were on the line.

So in a sense then the computer hardware was there, but the other aspects of technology did not allow for its effective use. And as Gaines has recently suggested, that microcomputers, because they are very powerful at the sites, may be more adaptable to these methods of analysis. At the Windover archeological site in Titusville, FL, which is under the direction of Glen Doran, they have utilized microcomputers effectively in the analysis of burials from this particular site. This site, you may remember, was the site that they recovered brains from individuals that had died about 8,000 years ago. And they have been able actually to use portable computers, small, hand-held computers, lap computers for the recording of data.

They can take this information then from the daily activity, plug it into their microcomputer and then transmit this information not only to their files but also to the main frame computer. And they have, in addition, to the computer in the field, they have computers at the location of the laboratories and those are connected to the main frame at the Tallahassee campus.

So that what happens then you can retrieve information from the site, and the laboratories can retrieve information from the site. People in laboratories can retrieve information from the site and from the main frame.

For example, I have been involved in analyzing some of the skeletal material from that site, and it will be possible for me when I do the chemical analysis to see, for example, where the bones were found. Is it possible that some of the—there is contamination in the bones or not, and they will actually be able to find information of this same type from the main frame computer at the University of Massachusetts.

I think this is quite important. This aspect of networking will allow completion to collaborate in areas that are quite distant. There has been more recent work with computers in dealing with site locations.

Information from previous archeological excavations, topographical variations in geography and ecological variations are put into fairly sophisticated programs, and this information then is used to not only locate the sites but also to provide for prediction of where other sites may be.

This aids in the survey method of the archeologists. This allows them to predict where sites are, and this increases the amount of time that can be involved in excavation of pertinent material.

Now, there are also some interesting new techniques in remote sensing that have been developed, and this involved other types of techniques. At the University of Massachusetts, Rick DeMer is using resistivity to analyze subsurface soils.

Can I have the next two slides?

Essentially what you are doing is using electricity and differences in the way in which electricity goes through the soil to mark areas. Those blocks are areas that have been tested and in the next slide we show you where you have subsurface changes.

This would be an area where you would expect to find some type of disturbance and the potential for archeological material is there. In fact, this was used at historic Deerfield on the site of—an excavation of an historic site, and they were concerned with not disturbing the area.

By using resistivity they were able to continue working in that particular way. This is from trubefori, again, in the Rift Valley, and this is from the satellite, and they were actually able to look at sites where they find fossils. In this case, the grey areas are the sites where most of the fossils were found.

So by using a technique such as this in other areas of the Rift Valley, they are able to predict where archeological paleontology remains may be found. I should mention in The New York Times yesterday they mentioned that they have been using seismographic methods connected to remote areas, sensing areas connected to high speed computers to determine what types of geological activities may have been involved in the formation of the Rift Valley itself.

Pasen Sheets at the University of Colorado at a site in Costa Rico has a cooperative contract with NASA which involves the use of remote sensing data, digital imaging, and other computer-assisted analysis. This information, with maps of the soil, precipitation, vegetation, land form, and so forth are digitized and put into the data base. So, essentially, what Professor Sheets can do then is to call up all of this information and again see what might be happening within that site with respect to human activity. He was able to successfully show that in this first area of analysis they found some long, linear areas which appeared to be somewhat strange and further excavation they were actually able to show that these were ancient roadways that were used thousands of years ago.

The AAAS, American Association for the Advancement of Science, has proposed and is involved now in a remote-sensing project in which they will utilize information to understand ecological changes that are occurring in Africa and other areas and this will be of interest not only to geologists but also to anthropologists, cultural anthropologists interested in adaptation to physical anthropologists interested in primate studies because you can look at changes in vegetation and so forth and obviously to the archeologists in trying to look at sites that might be found within a particular area.

Some of the future change that I would expect to find within the analyses and use of computers in archeology is that there should be improvement in the method of collecting of information. For example, it is possible now to utilize scanning sheets to incorporate information that can then be transmitted into a standardized format. This should reduce the time in intermediate stages of reporting. Eventually, when we find and are able to utilize voice-activated recording this will obviously improve dramatically and when the technology is there for computer terminals in the field, they can actually look at interpretations of changes that are occurring within those particular areas.

All of this would suggest that in the future we will probably find that the computer terminals for the microcomputer will become as much of a familiar aspect of the archaeological site as the shovel is now, or the pith helmet, or Indiana Jones, if you like that analogy.

There are some areas of use of computers in cultural anthropology policy that need special consideration. For example, there are some current debates as to the importance and use of machine readable data files. Much of this controversy centers around the human relations area file, which is housed at Yale University. This consists of information on 4,000 books, and on 250 societies and nations, and what they do is utilize essentially a fairly primitive format. They have information that is placed on pages and what they have done is they have computer notations along the pages, and they have generated bibliographies and sources of information, coding that information to provide information about the statistical information about cultures that can be utilized in certain types of analyses. There are many people who feel that this type of information should be machinereadable, and that it would have a much greater access.

Some of the statistical analogies are now possible. For example, someone could test out the fact, if there is a relationship between food, in relationship to a number of variables, and what they have found is that food taboos, dislike of certain types of food for symbolic reasons decreases with cultural complexity. So, now, they are utilizing the indexing of this information from these files, but the retrieval system is not computerized.

The most, I think, important work within cultural anthropology and the use of computer is the work of Oswald Warner from Northwestern University, and he has some special insights into the management of qualitative data that characterizes much of cultural anthropology. As a cultural anthropologist, you are going out and collecting verbatim accounts of activity or accounts of activities and also making observations. So, the ethnographic field studies, which are such an essential part of the anthropological studies, have created greater amounts of text material. This imposes significant tasks on the part of the anthropologist.

Bolton and Chambers estimate that a field trip of 12 to 18 months can produce up to $2 million worth of text equivalent to 8,000 pages of printed material. Since they have been able to determine that only about 50,000 words of text can be easily manipulated, new techniques of analogies are critically needed. I was just reading in the Anthropology Newsletter that Derrick Freeman has amassed 50,000 pages of notes on his Samoa studies, which began in 1940. So, what Warner is suggesting is that we have to have some means of retrieval of this information, and he is looking at the possibility of certain types of indexing and making some of this material machinereadable.

Part of the success of the ethnographer in this case is to be able to take the accounts, the verbatim accounts, which are essentially the individuals inside the culture looking out, and correlate it with the anthropological analogies. The anthropologist, sitting outside looking in, tries to see how these things can be cross-tabulated. What Warner suggested is that there still is a need for ideal hardware, that we have to have small, rugged computers with minimal moving parts, and there are numerous reports of the use of computers in the field where the floppy disk or the hard disk fails because of the damp or dusty field conditions. This seems to be a problem that anthropologists have, this amazing urge to go to the far away places that aren't very comfortable for the high technology that they might bring with them.

Messerschmidt, in a recent computer-assisted anthropology newsletter, described the difficulty of operating a computer in a remote area of Nepal. He goes through all of the changes in instrumentation necessary to maintain an eletrical supply that is reliable. And, so, I think you can see problems of this type.

There is a need in anthropology for a computerized bibliographic data base. We have the access to Eric, which is a very useful data base, which is the biological abstract, and we have access to science citation.

In the course of preparing for this testimony, I did computer searches on all three, which cost a total of around $9.50, but one of the surprising things was that about 20 important resources in references were missing, so we have those particular problems.

Now, in biological anthropology, there have been really profound changes in the methods of analysis. The availability of computer and statistical software has resulted in a shift from essentially descriptive research to research that is much more biologically relevant.

For example, we have seen changes in demographic research which has been enhanced by the computer. Eugene Hamill from Berkeley has used a gamut of techniques in computer analysis. He has used computer simulation, and even been involved in computer linkage.

This seems to be an extremely important problem, because you have vast amounts of data where you have birth and death records, you have to try to see if you can link these up to see if you can make an assessment about mortality in the particular population.

Alan Sweetland at the University of Massachusetts has utilized this computer linkage of this type to look at the impact of social cultural factors on fertility and infant mortality. What is important now is he has information from areas in western Massachusetts that goes back from the late 1700's up to the present. So you can see changes that occur in fashion.

The last example I want to go to involves computer activity in other areas. This is a site in the Andes, which Brook Thomas has worked on, and in this particular analysis, he was not only concerned with aspects of biological variation within the population, but he was interested in the whole question of energy usage. This is a market right outside this particular area.

What Thomas has done and why computers are so important is they have actually looked at energy flows within this whole situation. So, they have actually examined the amount of energy that goes into this population and how much energy is obtained from the population. I am not going to go into, obviously, details of this analysis, but what he was able to show, for example, is that the short stature of the people was adaptive. In other words, what he was able to show is that if you would have increased the height of these individuals by an inch, it would have necessitated 40,000 tons more of grain a year. This is not available, and would have led to the collapse of this particular site.

He has also been able to be involved in computer simulation of changes in fertility. For example, what he was able to show in this case is that if you increase fertility, your population is going to grow very rapidly, and if this happens, then it is not going to be able to be maintained at this location.

So what you have is alternatives. One alternative is that people will migrate out of that particular site. As part of their study, they started looking at the improved health that occurred within the population and found that this was also going to lead to certain difficulties, because if you take, for example, improve the health of women and children, line A, what you are going to get is very rapid population growth. If you improve the health of children, line B, you are going to get rapid growth. If you improve the health of the adults, you still get an increase in population. What this means is that we are obviously concerned with trying to improve health. What we should realize is it is going to have some impact on adaptation.

The last example I wanted to give you is to illustrate this aspect of change from descriptive studies that I would consider to be more cross-sectional. This is from a mesolithic skull in Sudanese that I helped excavate.

When material like this was first presented, the only method of analysis was to try to determine what racial group this skull belonged to. What we did is we were concerned with dealing with it from a different perspective.

We had the mesolithic skull on the right, and a more recent skull, 6,000 years younger, on the left. What we were interested in doing is trying to determine the types of changes that were occurring in this population, and what we were able to do is actually--

there are two ways of doing it, again—the older approach would be to take all the measurements from the skull, from the bodies, and put them into a computer program to determine distance of the population. What we find is this is much too descriptive and really doesn't tell us as much. What we have done is utilize the process of digitizing some x rays of the skulls, and what we can do then is generate all kinds of measurements.

Initially, we have dealt with this in two-dimensions, and with recent research, we are now able to move into three dimensions. This is going to have great significance within the whole area of physical anthropology, because what can now be done is we can get measurements, say, of a Neanderthal skull and not only look it at on a side dimension but facial view from on top, and it should greatly aid the study.

We have been able to actually look at the rates of change that occur. You can see that in the course of about 1,000 years, you are getting slight changes. But we are looking at changes from those mesolithic skulls to the more recent skulls, what we find is that the changes can be analyzed through multivarious statistical techniques.

We can take all the measurements taken on skulls and reduce them to essentially trace that in three areas. By analyzing the cluster, we can look at profound changes that are occurring, not only look at changes that have occurred, but look at them through time. So we can look at changes increased slightly cluster. One of those that stayed the same or decreased slightly, cluster two, and those that in cluster three that have changed dramatically.

When we do this, what we have actually found is, I think, similar generalizations that we can make. What is happening in this population is that there has been a reduction in the use of the facial muscles through changes in diet. So, what happens as these muscles change, what happens is that you get a shortening or a decrease in the size of facial apparatus; a head length decreases and you have an increase in cranial height. And what happens is then that essentially the face sort of rotates up underneath the cranium. I think what is important here is that this illustrates the types of changes that have occurred in the evolution of Neanderthals though modern man, and it suggests more active ways of dealing with this type of material.

I have also been involved in the analysis of mummified material from Egypt. This is a mummy going into a CAT scanner. This is a recent innovation, obviously. Computers play a great role.

What happens is that you take a number of x rays, and then you analyze them in a systemic fashion. We have looked at problems such as osteoporosis in this particular group, and we have been able to show that there is a nutritional aspect to osteoporosis in these populations.

More recently, Glen Conroy has looked at 30 million-year-old skulls utilizing the same technique. Not only has he been able to look at the structure of these skulls, but they can actually dissect away some of the matrix that are found, so they can actually do much more significant analysis that occurs within this area.

This is from a recent Science article. It talks about rapid changes that are occurring within the computer use in computer technology. What it really shows is that from the 1950's, there has been a four-generation change in the advancement in computer technology.

What I am concerned with as an anthropologist is that oftentimes, the scientists don't have the ability to incorporate those new techniques and new technologies into their repertoire of analysis. I think part of what we should be concerned with is trying to insure that anthropologists do have ability to be trained in these areas.

The other concern that I have is that as we do develop these new technologies, that they are available to the anthropologist and other scientists, because oftentimes, as technology increases, even though the cost per unit of analysis goes down, the equipment becomes overused in some sense and creates a particular problem.

In this cartoon, it says through about Taylor, I was blind-sided by the new technology. I hope that as an anthropologist, that we are able to evaluate this new technology and understand its importance, not only in this technological sense, but understand its importance in terms of the social system and the ideological system in which the populations who develop these machines live.

Thank you.

PANEL DISCUSSION

Mr. **Brown**. Do you have any questions, Mr. Slaughter?

Mr. **Slaughter**. No questions.

Mr. **Brown**. Gentlemen, I won't pretend that we understand all of the details of what you have presented with regard to our science, but I can assure you that the overall impact has been impressive, since most of us are not only ignorant about the computer field, but particularly about the scientific areas in which you have utilized the computers. So, it has been very helpful to us.

Dr. Langridge, one of the thoughts that went through my mind in your presentation was the question of how you characterize the molecules in order to produce the images that you demonstrated so well in those pictures that you had there? Is this a mathematical process or is this a process which you might call an experimental process in which you develop models of these images and then transfer them, translate into visual images?

Mr. **Langridge**. For the big molecules such as proteins and DNA, it begins as an experimental process, x ray to diffraction, and follows through a process very much like the process described for the telescopic image to generate the image of structure. We then start with that structure as the beginning point. There are attempts, and it is a major research project now, to make mathematical methods to do this in the computer without the necessity for the experimental work. So far, that remains a research project. It would have major impact not only from the molecular biological point of view, but within industry, something that the genetic engineering industry would have to be able to do, to predict the structure of a protein.

So far, we haven't succeeded.

Mr. **Brown**. This is a difficult question, but what is the relationship between the reality and the image, if I may ask?

Dr. LANGRIDGE. It is very close. It depends on what you mean by reality. What is a realistic image of a molecule we don't know, you can't see one. So we recreate a model in which the positions of the atoms are determined from this experimental research.

Mr. BROWN. That is accurate.

Dr. LANGRIDGE. That is accurate to within the limits of this experimental work, which can be quite great. You know the position of the atoms in some of the smaller proteins to a fraction of the distance between the atoms. You know them very accurately. On the other hand, the temperatures at which our bodies are, 37 degrees, at the molecules are moving, they are not static, they are not rigid things that you see. So, part of the impact of the development with supercomputers is in fact to be able to model that motion and to give you some idea of the computational difficulties. We are doing some computation on a Gray, and it is reported, I believe, you have that issue of the *Chemical and Engineering News*, on which we have another rather pretty cover picture.

Some calculations are being done on that, which it takes hundreds of hours to model a few picoseconds, a few fractions of a second motion of the molecule, and again, you need the graphics in order to be able to see what is going on.

That was the main essence.

Mr. BROWN. The graphics are a powerful tool, obviously, for your research purpose, but it seems to me just from the way you have utilized them in publication, they are powerful tolls for scientific education.

Dr. LANGRIDGE. Yes, sir.

Mr. BROWN. For the public?

Dr. LANGRIDGE. Yes, sir.

Dr. ARMELAGOS. I think the other aspect of the computer graphic also allows for a presentation of even standard graphic material like I presented, and to experiment with that is more interpretable, I think that is an important area, it is going to have great practical importance.

Dr. LANGRIDGE. Yes, sir.

Mr. BROWN. Dr. Vanden Bout, your description of the way in which you enhance radio astronomical images reminds me of or brings to mind the research going on in developing very large, lightweight segmented computer controlled mirrors for visual astronomy. Is there a parallel there? Does the same problem exist in a computer analysis of a very large segmented mirror as in the computer analysis of a segmented large array?

Dr. VANDEN BOUT. I assume the segmented mirror is visible like a telescope. If that telescope were used in, if its use were contemplated where those segments were driven individually to correct for the inhomogenity in the atmosphere, the answer is yes, that is what we are doing.

In any telescope, if the wavefront as it comes in through the atmosphere passes through an area that is inhomogenous or disturbed on a scale smaller than the telescope, then when the wave front hits the telescope, it won't be perfect, and there will be noise added due to the atmospheric disturbances. Now, adaptive optics is the word that is used to describe controlling pieces of a telescope mirror so as to take those disturbances out. That is a very active area of research now. All we do is put it in the computer. Instead of moving our antennas up and down on the ground to take care of these phased differences, we do it after the fact in a computer which is ever so much easier.

Mr. **Brown**. These questions reveal my ignorance more than anything else. Would it be theoretically possible to develop a very large optical mirror by making it segmented, that is, in discrete pieces, but controlled by a computer so that each piece——

Dr. **Vanden Bout**. Certainly.

Mr. **Brown**. Would that give a resolution in excess of what our present, say, 100 meter, 200 meter, what do we have——

Dr. **Vanden Bout**. The 200-inch telescope is the largest one that is operating now in this country, and there is a project in your State to build a very large, 10-meter diameter telescope that does have a so-called teselated mirror. This was a number of pieces and that project is underway. The computer control is intended to preserve the shape of the mirror, and I do not believe they are at this time planning to control those segments so as to remove the effects of the atmosphere. That is a much more ambitious project than simply preserving the shape of the mirror, but yes, certainly.

Mr. **Brown**. This leads to an unlimited perspective for the optical telescopes then, optical astronomy?

Dr. **Vanden Bout**. Yes, all sorts of astronomy. With the advantages presented by the computer, it completely turns the field upside down, I think. It has opened it wide up.

Mr. **Brown**. Have any of you gentlemen speculated about the definition of information, what it is that we really mean when we talk about information? In each of your sciences, of course, you are concerned with the accumulation of data.

Data is not the same as information. Information is not the same as knowledge. What fundamental things are we looking for here? What does it mean to the society?

Dr. **Langridge**. I think if you restrict your information solely to numbers, others even to letters, you will be much too restrictive.

The old adage, one picture is worth a thousand words is most certainly true. It applies to all fields. In the days when we used to have to deal with reams of numbers and make a model and put the models back in the computer, no connection with the visually and what was going on with the number, how we transmit as we are now the network, to transmit a picture, detailed picture is very expensive.

And that is one of the problems, of course, in which we are developing higher band width communication that becomes viable.

Mr. **Brown**. One of the fascinating things that has been presented recently is the concept that DNA may be more or less eternal, that we may have today genetic material that is the same as existed ions ago, and it has been transmitted, in effect, it constitutes a process of information flow over long period of time, and still is providing whatever this information provides, it directs the structure of life.

Dr. **Langridge**. There are certain parts of DNA that have over a long period, one can tell developmental studies which have been done. Of course, some parts of which are quite variable, fortunately.

We look around the room, and see quite a variety. In the city of Washington, you see a larger variety. I think there are those parts which essentially remain for a very long period, other parts which are able to change. I think it is that flexibility within the living cells—quite extraordinary. One of the things we would like to understand in detail.

Dr. **Armelagos**. Given the fact you have this ability to change, this restricted in terms of generation, you have within the living system, I think that is why it is useful when we are talking about information transmission within the cultural system, that is why it is so much more adaptive, that is why we see the give generations of computers that have occurred in just a portion of my lifetime. I think part of the interesting aspect and dovetailing of what happens within biological systems and cultural systems is quite important.

Mr. **Brown**. Is there something beyond biological systems, beyond cultural systems?

Dr. **Armelagos**. Well, I think——

Mr. **Brown**. You can envision the whole universe as an information-flow process?

Dr. **Armelagos**. Yes; this is information essentially what you are getting in organic information.

Mr. **Brown**. Astronomers are receiving information in some cases generated 16 billion years ago.

Dr. **Armelagos**. Yes, sir.

Mr. **Brown**. From Big Bang. All right, I am wondering if computers have any place in philosophy.

Dr. **Langridge**. Whether it does, I think is an entirely different question. Many of the programs that have supposedly demonstrated the ability to think really don't think. Any one of the people in the field of artificial intelligence or cognition would agree that this was indeed thinking.

The problem is as many of the people in the field have said, the more you define what the computer can do, the further away goes what you say it can't do. A human can do the things—the computer can do certain things, and you push the definition further and further away perhaps in a few years the computer will be the world's chess champion.

Does that mean the computer is thinking? I don't think so.

Dr. **Langridge**. Well, what I am really probing at here is something like a paradigm which so many people have now but we don't see what the paradigm is yet as far as information sciences are concerned. We see rapid and massive changes occurring and we haven't put it in a conceptual framework yet.

I think within science it is. Certainly within the area of science itself I have been exposed to. Most sciences regard a computer as something which crunches numbers, produces huge quantities of data, numbers, and I think the important thing is to regard the computer as a tool for solving problems, whether these involve numbers of symbols or pictures and whatever, I think gradually as that paradigm filters through science we see a much more flexible use of computers than we have today.

Mr. **Brown**. We still have to generate the problems.

Dr. **Langridge**. Oh, yes; still have to generate the questions.

Mr. **Brown**. Well, gentlemen, I wish we had more time to pursue this but other things intrude upon all of our schedules, I am afraid. I want to thank you very much for your contributions.

As I say, it has considerable impact even though it has taken time to sort out the details and that is what we are trying to do.

Thank you very much.

[Whereupon, at 12:30 p.m. the task forced adjourned, to reconvene at 10 a.m. Wednesday, September 11, 1985.]

THE IMPACT OF THE INFORMATION AGE ON SCIENCE

WEDNESDAY, SEPTEMBER 11, 1985

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE AND TECHNOLOGY,
TASK FORCE ON SCIENCE POLICY,
Washington, DC.

The task force met, pursuant to call, at 10:07 a.m., in room 2318, Rayburn House Office Building, Hon. George E. Brown, Jr. (acting chairman of the task force) presiding.

Mr. BROWN. We will try to get the task force started and invite the witnesses to come to the table, if they will.

This is the second day of 3 days of hearings on the subject of the impact of the information age on science. We opened up yesterday with some extremely interesting testimony by a number of distinguished witnesses, which I think helped the members of the panel a great deal in understanding the vital importance of some of the achievements which we generally refer to broadly as advances in information science and technology. We, I think, have a much better understanding of how these advances are both being produced by and used by the scientific community.

It has been called to our attention, as an example of this, the work that was just announced at Purdue University, where researchers at least claim to have solved the mystery of the structure of the common cold virus, giving scientists their first clear look at one of the most troublesome and universal disease-causing viruses known. This breakthrough was achieved through the use of computers, and it is asserted that it might have taken 10 years without the use of a supercomputer, which I think is striking testimony to the use of supercomputers in scientific research. That will particularly appeal to Members of Congress who are afflicted by the common cold. [Laughter.]

Our first panel member this morning is Dr. David Pensak, who is research supervisor for Computational Chemistry for E.I. du Pont de Nemours—I guess that is the DuPont Company—and he is in Wilmington, DE. Following him, we will have Dr. J. Freeman Gilbert, professor of Geophysics at University of California at San Diego, and Dr. John Hubbard, professor of Mathematics at Cornell.

All of you gentlemen are welcome here this morning. We are very happy that you could find the time to do this. I note that our distinguished ranking member is entering the room, and I will ask him if he has any comments to make before you get started.

Mr. LUJAN. Go right ahead.

Mr. Brown. Thank you.

Dr. Pensak, you may begin, then.

STATEMENT OF DR. DAVID PENSAK, RESEARCH SUPERVISOR, COMPUTATIONAL CHEMISTRY, CENTRAL RESEARCH AND DEVELOPMENT DEPARTMENT, E.I. du PONT de NEMOURS & CO., WILMINGTON, DE

Dr. Pensak. Mr. Chairman, I am grateful for the opportunity to speak to you today.

I would like to try to describe for you some of the frontiers of computing as they apply to problems in scientific research and development. I will be addressing them from the perspective of a chemist, but I really believe that much of what we have to say is applicable to other fields as well. I have to point out that these are my personal beliefs and opinions and must not be construed as representing those of my employer.

While many of my associates would consider it heresy, it is my belief that the fundamental nature of chemical research has not changed greatly since the dark ages. We have tens of thousands of new chemicals, highly sophisticated and sensitive instrumentation, and a detailed theoretical understanding of how molecules behave. What we do not have is any set of good, generally applicable heuristics that can help us go into the laboratory and make a new molecule which will have the activity we want. In the agricultural chemical area, we refer to it as the "spray and pray" philosophy. [Laughter.]

Experiments that fail quite often provide no information whatsoever to us, and there is no journal of failed experimentation. The nice thing about the computer is that it gives us the opportunity to build a conceptual model for our experiment, such that research which fails can still give us new insight and help to narrow down the areas that we should be looking at.

Now, it has been established by psychologists that the way we think about a problem is controlled by the mental data structures that we build when the information is first presented to us. When you take your basic organic chemistry course, you see a cyclohexane molecule drawn as a nice equilateral hexagon, looking very much like a ceramic bathroom tile. And even though in succeeding courses you learn that that is not a chemically correct representation, you still wind up drawing it that way on a sheet of paper because that is the notational form that you are most used to communicating it to other chemists with. So part of our problem is to find ways to get the chemists to think in terms of chemical reality, and that is where the computer is particularly important.

It has also been established that there is only a limited number of dimensions or variables that the human brain can handle at any one time in trying to make a decision. The computer again is unique in providing significant flexibility in how these variables are presented.

It has been said that the human brain can handle 4+ or −2, simultaneous independent variables when making a decision. We have an in-house joke that if you can handle six at a time, you are an Einstein; if you can handle two at a time, you are a candidate for management. [Laughter.]

Mr. **Brown**. If you can handle one at a time, you are a candidate for Congress. [Laughter.]

Dr. **Pensak**. So we have been working on ways to try to represent higher dimensionality data in a way that you can look at and see. For example, we have developed a way to represent a six-dimensional data space on a sheet of paper. Your X and Y axes are as normal, but your third dimension is represented by a letter of the alphabet, A to Z; the fourth dimension is the size of the letter; the fifth is the color of the letter; and the sixth is the rotation of the letter around the axis that is pointing toward you. What we have discovered is that you can see patterns and trends in six dimensions, but we have never learned how to communicate that to one other. The human brain has never been forced to do that, and the vocabulary doesn't even exist. So the computer is giving us a way to make sure that everybody sees the same thing and can manipulate the images to be looking at the same problem.

Now, there are four specific areas where there needs to be a better interaction between computers and science, and I would like to describe each of these for you individually.

The first is algorithm design, or the way in which we perform specific computations. Computers have made a significant change in the way we actually perform the numerical operations. There is a class of computation on matrices which is called an eigenvalue calculation, and there is a very simple technique which is taught in all the basic numerical analysis courses for doing it, so you can do this by hand. This was appropriate when people just had desk calculators. But now that we have machines that are literally millions of times faster, those algorithms are no longer the most efficient. In one case that we recently looked at, using the old procedure was 500,000 times slower than the new procedure on the same hardware.

In the area of optimization, you see a similar kind of thing. There are new techniques for linear programming which are helping the airlines schedule flights more efficiently, helping the phone company set up routings. If you compare the simplex technique—and the old one is taught even in business schools today—with the new projected mapping techniques such as are being worked on at Bell Laboratories, you see that it can be as much as 10 million times faster, enabling us to look at and possibly solve problems which we just cannot do any other way. So it is really making a fundamental change in the way we look at things.

We have often been asked, are there any molecules which du Pont is currently making, which were designed by computer, which are making money for you? And our response to that is a molecule which was designed by a typewriter.

The computer is nothing more than a tool to help us understand the data that we are dealing with. People create; humans do not. But the computer gives us a chance to do this much more effectively than we would have otherwise.

Think, if you will, in the area of interactive graphics, about a weather map. Look at how much data is actually conveyed in that one small graph through some very special symbolism. You can look at a weather map and, in a matter of seconds, see whether you want to go out and play golf today, and yet there are literally millions of data points which are involved in that. We desperately need more research in trying to understand how to present more complex data than just the weather, and the computer, we think, can help in that regard.

Imagine that you are flying over the Rocky Mountains. You get one perspective of the terrain. If you drive through them, you get a different perspective. If you look at a National Geographic Society map, you get a third perspective. Now, which of these is correct? It is really that all of them are, but they are conveying different kinds of information to you. The nice thing about the computer is it gives you the way to look at a variety of data representations to see what generates the new idea in you.

Related to this is the question of large data bases of information. You have seen these information retrieval systems where you request a specific piece of information, and it either comes back with the value or "We don't have that information." But how often have you been looking for something in a journal, and you see a piece of information which, to anyone else, would appear unrelated, but it generates an idea in your head. So we have to find better ways to let people look at data which doesn't precisely answer the question but comes close. The computer can really help stimulate new ideas from people.

Now, you have probably seen the plastic models of molecules. They sit back quietly on your desk, and they don't move. But when you start to deal with very large molecules like enzymes, you can be dealing with a structure which can be 8 to 10 feet high, weigh several thousand pounds, and has taken literally weeks to build. Your willingness to go in and make small changes to that model to see what the effect of changing an amino acid or the twist in a protein, you just won't do it. But since the computer can generate these pictures in just a matter of seconds, then you are willing to go out an try experiments, intellectual experiments, that you would never even think of before.

Now, if you wanted to look inside the molecule at the receptor site where the drug actually interacts with the enzyme, you would like to be able to take your molecule, the enzyme, and run it through a band saw with an 80-inch throat and just cut it in half. Of course, you don't want to do that. The computer gives us the ability to do that.

Another thing which is very nice about the computer and these molecular models is, if you look at a traditional model, the hydrogens are white, the carbons are black, because that is the way the corporations that make the plastic sell things. But there is no reason that it has to be that way. We have found that by color-coding to represent any of a variety of properties, you can see things in your molecule that you could just never see any other way, such as charge distribution on the surface of a catalyst. It works out to be remarkably effective.

We have been seriously considering buying something like a pilot flight training simulator, because if you think about the computer computations which are involved, there is nothing conceptually different about landing an airplane on a runway and landing a drug molecule on an enzyme receptor site. My management finds some of this a little bit farfetched, but they are willing to pay the freight, so they are clearly committed.

The question is, how do we actually design molecules? Traditionally, you will take two models, one in this hand and one in that, and squint and look for the similarities between them. Well, that works really well if you only have two molecules, but if you have more than two, it is a physical impossibility to do that. The computer, however, doesn't care and gives us the ability to superimpose a large number of molecules on top of one another and look for the similarities and differences.

To put this in physical terms, if you look at any instrumental-based signal, there is a certain amount of noise which is inherent in that, and if you keep taking the signal over and over again, the noise averages out to zero. We have been able to develop the concept of molecular noise and show there are certain parts of the molecule which correlate with activity and other parts which are there only to get the important part to the right shape and nature. The computer lets us do this. It is something that cannot be done manually.

So an example of what this will let us do—we have been concerned with some of the brain peptides called enkephalins, and if you compute the lowest energy form of the enkephalin, you see that it doesn't look anything at all like the morphine molecule that this places in the brain, and we are able to compute now how much energy it costs to get it into the right shape to perform the same mode of biological action, and this has explained to us why a number of the enkephalins with substituents which would normally produce antagonist behavior have been totally ineffective as narcotic replacements.

Computer hardware is also going to play a very big role in the way scientific research is done over the next few years. John von Neuman has certainly left his mark on the field, but the architecture of computers that he proposed 20 to 30 years ago is no longer cost effective, given how inexpensive processors and memory are.

Now, DARPA is currently having a 65,000-processor system being built for the autonomous land vehicle project. The computations which are done in that are no different than would have to be done in looking at how two molecules would react with one another.

Personal computers are also playing an ever bigger role in the way research is done, and there is a fear held by some that once everybody can have a personal computer sitting on his desk, there won't be any need for the big computers, supercomputers, and we think that is exactly opposite of the case. A recent study showed that the demand for computing at a central facility goes up at more than 2½ times the rate that you have added capacity by the personal computers in people's laboratories. Once people can try things out there in their laboratory, they are willing to try bigger, more audacious calculations and, hopefully, start computing things which are somewhat more realistic. We are having to deal with very simple cases right now.

Another problem which is important is artificial intelligence. There has been a massive amount of hype and hot air about artificial intelligence. There is a poster in my office that says, "It has taken artificial intelligence 25 years to become an overnight success."

There is a belief that all you have to do is just put your information into the computer now, and an artificial intelligence system will magically tell you what the solution is. I would like to give you some examples of why that is not the case and why there is a significant need for research in artificial intelligence as it applies to all the scientific disciplines.

Observe the following two sentences: "John loved Mary, so when he saw the truck coming, he pushed her." "John hated Mary, so when he saw the truck coming, he pushed her." Now, nowhere in either of those sentences does it tell you which direction he pushed Mary, but I would contend that you know instantly in which case he pushed her into the truck and which one, away. If we don't yet understand how we do this ourselves, it is very difficult for us to do that on the computer.

Robotics has also been touted as something which is a technology that is here now, that will fundamentally change the way we do chemistry. Again, that is a gross overstatement. Imagine the robot was sitting next to you, and you asked it to pass the pitcher of water. Precisely what you told it is that you want some water, and it might try to actually pick up the water. You have to tell it to pick up the pitcher of the water. You have got to tell it which hand to do. Just training a robot in simple table manners is beyond the current state of the art.

Another problem that we have to face is that computers have got to generate their own world model of the data that they are dealing with. Once you have learned a foreign language, you will find that you still do not think in that language; you always revert back to the first language you were taught for doing your thinking. The same thing is true for computers. We are being forced right now to program in a language which is different from how we think and is different from how the computers have to represent it.

So, basically, the computer, as we see it, will let us compute numbers infinitely faster than we have ever been able to do before. Bear in mind, however, that computing is not a substitute for thinking. Just because you can compute 10 times faster than you did before doesn't mean you will get 10 times the scientific content out. But we can hope. It will let us see things differently than we are used to seeing them. It will let us represent them in different ways than we have ever done before. And it will either let us or force us to think about things in terms of generic concepts and relationships that we have never been able to do before.

Let me give you an example of that. There is a large data base of x ray crystal structures which is maintained by Cambridge University in England, and as that is distributed, they try to make it machine-independent, so that to retrieve one structure from that data base takes about 30 minutes of computer time. It is a very large data base. We rewrote that software to be as machine-dependent as we could for a specific kind of machine that we had and brought the time down to less than 1 second on the same hardware. When you start to make a three-orders-of-magnitude speedup in how you can access your data, people start using it in ways you had never thought of. So a number of applications of this data are now in existence in our organization which nobody had even dreamed would be possible. It is all because we had the equipment there. But, like children with a sweet tooth, the more we do, the more we want to do, and that is why there is an ever-bigger demand for larger, faster, more powerful computers.

These are exciting times to be a scientist. We are, I think, approaching the point where our own intelligence can be a limiting factor on our ability to create, not the capriciousness of experimental observation. To simulate the hand-in-hand development of computer technology with basic scientific research will provide a unique environment for our ability to successfully compete in an evermore technologically complex world.

There are three specific areas that I would like to see the Government play a role in in order to facilitate this kind of growth. First, we are seeing that it is extremely difficult for academic institutions to get funding from Federal agencies for basic methodology development. It seems to be much more exciting now to try to apply today's technology to new areas where it hasn't been looked at before, not to try to come up with still faster and better algorithms for doing things we think we know how to do.

The interactions between industry and the academic community are only loosely organized, except when the universities are trying to raise funds. I would like it if Congress could mandate and fund some kind of forum to establish better communications between the universities and the academic community. This would give the universities better access to expertise and practical data which can be of significant interest to the entire economy and would give industry a more efficient way to tap the expertise which, as taxpayers, it has been paying for for a number of years. In addition, I think it would probably decrease the flood of faculty members who are quitting universities right now for the lure of large industrial salaries and facilities that universities cannot maintain by themselves.

And, last I would hope that Congress should mandate greatly increased efforts in trying to get the mountains of data which are sitting in the literature right now in machine-readable form. Experimental information that exists only in printed text or graph is of absolutely no value if you don't happen to know what that reference is or know that it is even there. By sharing nonproprietary data and computer programs, I believe we will have an immense leverage over working individually.

That ends my prepared remarks, but I will be happy to answer any questions that you might have.

[The prepared statement of Dr. Pensak follows:]

Proposed Testimony Before
Congressional Science Policy Task Force
hearings on
The Impact of the Information Age on Science

September 11, 1985

David A. Pensak
Central Research and Development Department
E. I. Du Pont de Nemours, Inc.
Wilmington, Delaware 19898

Mr. Chairman, I am David Pensak. I am the supervisor for computational chemistry in the Central Research and Development Department of E. I. Du Pont de Nemours. I am grateful for the opportunity to speak to you today.

I would like to describe for you some of the frontiers of computing as they apply to problems in scientific research and development. I will address them from the perspective of a chemist, but they are applicable to many other fields as well. I must point out that these are my personal beliefs and opinions and are not official policy statements of my employer.

While many of my associates would consider it heresy, it is my belief that the fundamental nature of chemical research has not changed greatly since the middle ages. We have tens of thousands of new chemicals, highly sophisticated and sensitive instrumentation, and a detailed theoretical understanding of how molecules behave. What we do not yet have is a generally applicable systematic way of designing new molecules. With limited heuristics (or rules of thumb) we go into our laboratories and synthesize plausible materials and then test them. Experiments that fail quite often provide no information whatsoever.

It has been established by psychologists that the way that we think about a problem is tightly controlled by the mental data structures that we build when the underlying conceptual information is first learned. For example, in basic organic chemistry we are shown the cyclohexane molecule represented as an equilateral hexagon, looking very much like a ceramic bathroom tile. In later courses we learn that that is an idealized representation chosen only to communicate a concept, not depict molecular reality. Nonetheless, many chemists continue to use this unrealistic representation while designing their research programs. The computer is unique in its ability to permit facile display of molecules in accurate form, as fast or faster than they can be drawn by hand.

Psychologists have also established that there is a limited number of dimensions or variables that the human brain can handle when trying to make a decision. The computer is again unique in that it permits significant flexibility in varying how the variables are presented, thereby increasing the chance that the scientist will see underlying relationships in his data.

Most people are quite comfortable in dealing with two dimensional data such as graphs. A few can manipulate objects in three dimensions. There is a real need however to be able to "understand" data in much higher dimensions. Take, for example, an effort to design a new building material as a wood replacement. There are roughly ten parameters that are measured for structural behavior of wood and there are literally dozens of different woods in daily use. To detect the holes or gaps in this property space goes far beyond the capability of most scientists or engineers. Interactive computing and graphics can greatly aid this and leads to much faster problem solution.

The challenges to more effective synergism between computers and science fall into several different domains. I would like to describe these separately.

Algorithm Design
Interactive Graphics
Hardware Design (Computer Architecture)
Artificial Intelligence

Each requires a level of cooperation between disciplines that will succeed only if there is a two way transfer of technology at a very high level and in very large quantity.

Algorithm Design

There are certain fundamental mathematical operations that get performed repeatedly during a chemical calculation. The majority of these are operations on matrices. Years ago, the procedures for doing these were designed for the convenience (and accuracy) of the scientist working with a desk calculator. These are by no means the most efficient (or the most accurate) for implementation on computers. For example, there is a technique that is taught in schools to find the characteristic values of a matrix. It is easy to understand and quite straightforward to perform manually. It is, however, extremely inefficient, especially for large matrices (much larger than one would ever do by hand). There are newer procedures that are almost incomprehensible to the beginning student (or even non-specialist) which are hundreds of times faster. Non-specialists rarely become aware of these advances until they appear in program libraries like those developed at Argonne National Laboratories.

In the area of optimization, a lot of progress has been made. From the early days of the simplex method we have progressed to new techniques that can be as much as ten thousand times faster. In modelling physical structures by the finite element technique, the multigrid methods are almost ten million times faster than the earliest algorithms on the identical hardware.

Even apparently small improvements in an algorithm can make a large difference as the complexity of the problem grows. There is one class of matrix operation performed in molecular orbital calculations that used to require computer time in proportion to the fourth power of the size of the matrix. The latest techniques have reduced that to about five times the third power of the size. For small matrices this is not significant, but for large, real-world, simulations the matrices can be on the order of several hundred, yielding more than two orders of magnitude improvement.

Interactive Graphics

The human mind has been well trained over millions of years to see and understand graphical images. The most common response of any technical person when presented with even a small amount of data is to graph it. A host of new techniques are necessary to permit scientists and engineers to be able to "see" large quantities of data. Take as an example the familiar weather map. There are literally millions of data points used in generating the map. Notice how special symbols and descriptors permit the communication of both the statics and dynamics of our weather in an extremely rapid manner. We desperately need research in how to do the same kind of presentation and depiction for scientific data.

The ability to represent complicated data even in three dimensions will be an important frontier for graphics. If you look at a map of the Rocky Mountains you get one perspective of the terrain. If you fly over them, you get a different idea, and if you drive through, you get still another impression. Which one is right - they all are. Which one tells you the most - it all depends on what you are looking for. It is vital that the end user of the data be able to easily choose between these (and of course other) ways of presenting his data.

Small molecules are easy to visualize since they contain at best a few dozen atoms. At the other end of the scale are proteins and enzymes, often comprised of tens of thousands of atoms. It is, of course, possible to build a physical model of an enzyme. They will weigh several hundred pounds, stand about 6 feet high, and cost several thousand dollars to build. Usually they have to be supported by an external structure to keep them from collapsing. Compare this to a computer generated image which takes only a few seconds to generate. There are many things that you can do with the computer which you can not do with a physical model. For example, suppose you wanted to take a slice from the front of an enzyme to "look" inside. Clearly you are not going to pass the entire plastic model through a bandsaw with an 80 inch throat - and yet you can do it trivially with interactive graphics.

You have all seen plastic models of molecules. They sit quietly on desks and do not move. Are they an accurate representation of physical reality ? Of course not; molecules are in constant motion except at absolute zero. The models are therefore, at best, a partially correct picture. Computer simulation offers the ability to visualize the actual behavior of molecules at any temperature.

How are molecules designed by man ? Often the chemist takes two models, one of a proposed structure and one of a known structure with the desired properties. He holds them in front of his face and squints until they are superimposed. The similarities (and differences) are then apparent. This procedure does not work for more than two structures because we have only two eyes (and we can not ever physically superimpose two objects). The computer, however, is not encumbered by this restriction.

Consider, if you will, an experimental signal which is somewhat obscured by noise. By repetitively acquiring the signal and averaging it over time it is possible to extract a "clean" signal from large amounts of noise. A similar operation is possible in dealing with molecular structures - a vital capability in design of new materials. This can not be duplicated manually.

Hardware Design

John von Neuman has left the computer field a magnificent legacy in his description of the basic structure of a computer. During the early days of computers, this way of building computers was economically and technically the most effective and efficient. Today all the rules have changed. Microprocessors are becoming ever less expensive. The possibilities to organize arrays or networks of computers to tackle problems cooperatively or concurrently are enormous. It is no longer outlandish to dream of a computer with 65,000 processors. In fact, such a device is currently being constructed for DARPA as part of the Autonomous Land Vehicle project.

Many of the procedures that we currently are forced to execute on supercomputers could in fact be executed simultaneously on large numbers of relatively inexpensive microprocessors with far greater cost effectiveness. Does this mean however that there is no need for future supercomputers ? Not in the slightest. As the individual's ability to develop and evaluate techniques for modelling small systems grows, our ability to visualize and ultimately evaluate exceedingly complex systems will also grow. The impossible dreams of our current generation of scientists will become realities when ultra computers, several orders of magnitude faster than today's supercomputers become available. To describe it in physical terms, if you have a need to transport very large numbers of people, it will be most efficient to spend your money purchasing a fleet of bicycles. If you have to move just one person rapidly, it is better to have spent your money on a fast automobile. This country is in the very fortunate position of having the resources to do both, and to be in the position of being able to choose between them.

Artificial Intelligence

There are as many different definitions of artificial intelligence as there are practitioners in the field. Let me use as my definition the simulation of those thought processes that are practiced by a human being that involve judgement and planning.

Many of the problems that we need to be able to solve require wisdom that we don't yet understand in ourselves - and therefore can not simulate. For example, consider the two sentences.

John loved Mary so when he saw the truck coming, he pushed her.

John hated Mary so when he saw the truck coming, he pushed her.

Nowhere in these sentences is there any information that will permit today's computers to infer that in the first case he pushed her away from the truck and in the second case it was towards the truck. And yet, I will guarantee that none of you mis-interpreted either of the sentences. The nuances of language can have extraordinary complexity.

Things that we currently take for granted are also far from simple. Consider the simple act of passing the butter. You do not consciously go through any formal procedure to choose with which hand to pick up the butter plate (assuming, of course, that you don't just grab the stick of butter directly, even though it was the object that was asked for) and then decide how to pass it through on its way to the person who requested it. The effort required to explicitly program in the most simple of table manners for a robot is prodigious.

The next generation of computers and software will have to be able to develop their own "world model" if they are to exhibit any real "intelligence". Just as we can not force someone to think in a language other than their own, we can not program computers to "think" unless we let them construct their own forms of knowledge representation which will be most convenient for them. Is this do-able in the next two or three years - probably not, but it is a direction that will clearly have to be explored.

In conclusion, the computer has the ability to revolutionize how we think about our problems in several ways.

It can enable us to compute numbers faster than we have ever been able to do before.

It can let us see things differently than we are used to seeing them.

It can let us represent "things" in different ways than we have been able to represent them.

It can let us (or force us) to think about things in terms of generic concepts and relationships in a way we have never been able to do.

The impact of today's computing technology on problems of science and engineering is already enormous. We are becoming able to simulate some physical systems when it would be prohibitive or even impossible to perform the actual experiment. We can speed up or slow down time to study phenomena that we can not yet measure. We can, when necessary, run time backwards during a simulation to try and understand why certain physical events took place.

Like a child with a sweet tooth, the more we do, the more we want to do. As we are able to model small systems we learn enough to contemplate (if adequate computational resources could be available) reliable modelling of much larger systems - ad infinitum.

These are exciting times to be a scientist. We are approaching the point when our own intelligence will be the limiting factor on our ability to create, not the capriciousness of experimental observation. To stimulate the hand in hand development of computer technology with basic scientific research will provide a unique environment for insuring our ability to successfully compete in an ever more technologically complex world.

Policy Recommendations

There are three specific recommendations that I believe would catalyze the kind of explosive growth in research and development that we all seek.

(1) It is extremely difficult for the academic institutions to get funding from Federal agencies for basic methodology development. Application of existing technology to new domains of science is receiving much higher priority. This is mortgaging the future to pay for the present.

(2) Interactions between industry and the academic community are only loosely organized except where the universities are trying to develop new funding sources. If Congress could mandate and fund some kind of forum to encourage better communications, all sectors of the economy would benefit. Universities would have better access to expertise and data relating to practical problems, and industry would have a more efficient way to tap the expertise that has been developed in the academic community. In addition, it is probable that this would decrease the flood of faculty members who are quitting to work for industry (which is again mortgaging our future).

(3) Congress should mandate greatly increased efforts in making the mountains of data already obtained much more accessible via electronic methods. Data that exists only in a printed text or in a graph is going to become relatively worthless because it can not be easily found or accessed. By sharing non proprietary data (and programs) we will have an immense leverage over working individually.

Mr. Chairman, this ends my prepared remarks. I will be happy to answer any questions.

David A. Pensak
DuPont Co

Modeling system cuts wasteful steps from complex R&D

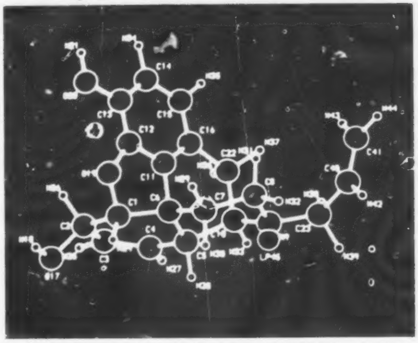
A practical and effective computerized modeling system relates expected properties to structures of complex chemicals. The system handles many types of programs after minimal modification.

MUCH OF THE MONEY designated for research, says Dr. George T S. Wolken Jr. (*IR&D*, October 1980, p 157), is used to synthesize products and to develop processes that never will be used. But if we can predict properties of a proposed compound and know that these properties will not be sufficient for a given application, then we will not have to go through a tedious and wasteful synthesis of that compound.

Today, chemists are turning more and more often to computers to make these predictions and to compare chemical structures for similarities and differences. A recent article (May 1982, p124) has noted that scientists already have developed a large number of programs for these purposes. But the programs have been developed quite independently of one another—and they are rarely compatible with one another.

Many of these modeling programs provide only one special computing function. Often, that function is designed to produce only one particular type of structure. As a result, such programs are unlikely to be usable as received by any given research organization.

Such programs often have been writ-



The "Build" program of the molecular modeling system has been used to remove the methyl group from a displayed stick model of the morphine molecule and replace it by an allyl group.

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[redacted]

Display of a typical color-coded space-filling model of morphine resembles a 3-D model familiar to organic chemists. Color is particularly important in this type of model since it helps the researcher to visualize the relationships of the various kinds of atoms that make up the molecule. The software system ties together all components of the molecular modeling system hardware to insure their efficient operation.

ten to run only on a specific computer; they frequently are not compatible with the computer that the organization happens to have at its disposal; and the programs may involve a wide variety of more or less "standard" data-entry procedures.

Moreover, currently available analysis programs tend to stress numerical data as the final product, while organic chemists are accustomed, by training and practice, to working with the conceptual and the pictorial. In general, if researchers are to concentrate on chemistry, they should not be burdened with the details of computing procedures in the process of molecular modeling techniques.

A research organization, therefore, can make most-effective use of available modeling programs and can provide truly productive tools to its research staff by integrating individual programs into a chemistry-oriented software network. To accomplish this, researchers will need to standardize data-entry procedures in a form that is consistent for all programs.

Data-output options must be greatly expanded beyond numerical printouts in order to offer a variety of graphics tools for visualizing and manipulating molecular structures.

Experimenters should be able to rotate, to compare, to translate, to shrink or enlarge, and to modify three-dimensional images on a cathode ray tube (CRT) screen, and then to direct the computer to analyze the images they see. And to provide chemists with the degree of flexibility and control that they need in this process, application of the modeling tools must be highly interactive.

Modeling hardware. As hardware to handle the modeling programs, we have chosen a Digital Equipment Corp. VAX-11/780, plus an Evans & Sutherland "Multi-Picture System," a high-performance interactive graphics package. This combination permits the experimenter to perform real-time rotation and translation of molecular images on the screen.

Most of our laboratories use either Tektronix 4014 or 4010 graphics terminals or devices that emulate them. Finally, color raster-display devices, Advanced Electronics Design Model 512, are used to produce color-coded space-filling models of organic molecules.

We have to emphasize the importance of color in molecular modeling. Videodisk recorders and video-tape players are available to record both static and dynamic displays of molecules. The software system has to tie together all of these components to permit their operation in the most efficient manner.

"Tribble" system. The development of a software system must, of course, attack the problem of many independent, disparate modeling programs that already exist. To minimize the software investment, we at DuPont have chosen to modify acquired programs ar little as possible.

Thus, we have been able to concentrate on writing software modules that provide consistent data entry, expanded graphics output, and effective interaction between the experimenter and the modeling program.

To provide a library that includes all information needed by any and all modeling programs, we have set up a molecular de-

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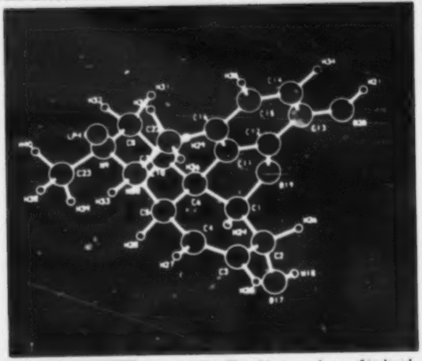


A typical stick model shows the 3-D relationships of the various atoms in the molecule. Molecular mechanics software permits rotation and translation of the various components of the diagram to illustrate a molecule with minimized strains (most probable configuration).

scriptor file. This file is made up of individual records, each of which contains the spatial coordinates and describes the bonding of the atoms in a specific molecule.

Each of the records is assembled in the same way, no matter how complex the particular molecule may be, without regard to the particular modeling program that is used to obtain the information.

From the information, the data-generation modules in the system generate input-data files in whatever form is required by a specific program. Each analysis program provides a full numerical file that can be fed to other programs or printed out on a line printer.

In addition, it usually is necessary to write other output modules that will generate a summary output file and a graphics output file. The summary output file supplies to the chemist only the information needed for a given experiment. The graphics output file, as the name suggests, permits graphics output from acquired analysis programs that did not provide for this facility when they were acquired.

Before any acquired modeling program can run, we have to convert the machine code in which it was written to run on the host computer. Occasionally, this may be a trivial task. But, in most cases, the conversion to a code acceptable by the computer can be quite difficult.

Since the molecular modeling system in the DuPont central research and development department is "the chemist's best friend," I have named it "Tribble"—for my dog, named for a creature in the *Star Trek* television series. All of the 300-plus programs in the system are available to any chemist in the company through graphics terminals of various types.

Image generation. In using the system, the experimenter enters information that describes a two-dimensional sketch of a molecule or of that portion of the molecule of interest. The system assumes that all atoms are spherical and that the atomic sizes are those characteristic of each particular atomic type.

The linkages between atoms are treated as springs. Bond energies are calculated from force constants that can be associated with the different types of internal coordinates. By comparison of the force constants of previously unknown compounds with those of known molecular structures, it is possible to predict accurately the structures of the unknown materials.

The modeling system also contains several other types of acquired analysis programs. Among these are programs for pattern recognition, for statistical calculations, and for quantum mechanical treatment of data. In addition, 16 different molecular-orbital-theory programs treat electron-energy levels and electron distribution in isolated molecules or in molecules undergoing reaction.

Experimenters in the central R&D department use the system primarily for the generation of graphic images of various molecular structures and for the manipulation of the images in several different ways.

For example, molecules can be displayed as stick models, as ball-and-stick models, as surface (dot-cloud) models, and as space-filling models that take advantage of computer-enhanced color. As still images, the various structures can be viewed from any angle. Alternatively, the operator can rotate or translate the images in real time.

The 225 or so software modules we have produced to date are, in general, much shorter than most of the modeling programs we have acquired from outside sources. In fact, few of the new modules exceed 1,000 lines of "Fortran." By adapting existing programs to run on our equipment, we have avoided the necessity for writing large numbers of lines for extensive programs.

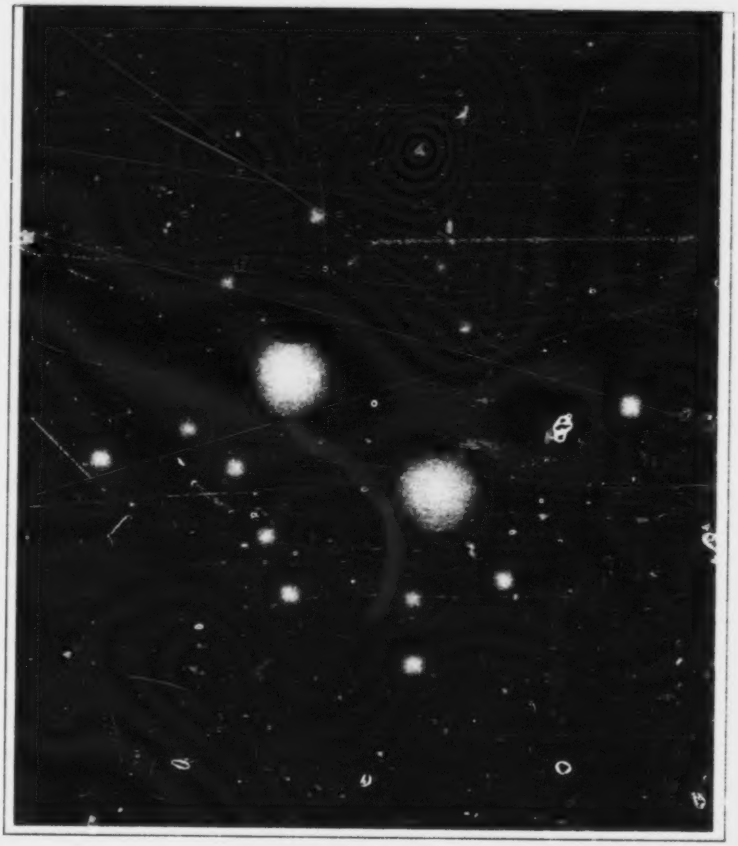
Descriptor file. In order to use the Tribble system, the operator sets up a molecular descriptor or connectivity (Con) file. This is accomplished either by drawing a two-dimensional sketch on a CRT screen and then performing a molecular-mechanics energy minimization, or by transferring a known molecular structure to a Con file from one of the three data bases acquired from outside sources. The outside files we use are:

☐ Cambridge Crystal Files—a library of more than 28,000 x-ray crystal structures, including the programs to search and to manipulate them.

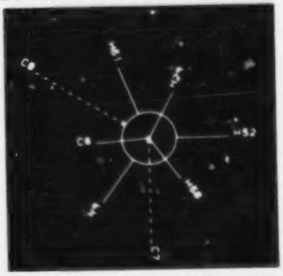
☐ Protein Data Bank—complete x-ray structures for about 150 proteins and enzymes, compiled by Brookhaven National Laboratories.

☐ Protein Sequence File—all published primary sequences of proteins and nucleic acids, maintained by the staff of the National Biomedical Research Foundation.

These files help experimenters by revealing ranges of possible conformation of



"The picture shows a computer-generated display of a Du Pont triethanolamine titanate as developed by Du Pont research using x-ray crystallography and color molecular graphics. For clarity, hydrogens have been omitted and carbon radii reduced by half. Du Pont 'Tyzor' organic titanates are used for crosslinking, catalysis and surface modification. For more information, write to Du Pont Company, N-2470A, Wilmington, DE 19898"



Chemists who are familiar with Newman projections may request this type of model that will show the area in which they may be interested. The example above is a projection along the bond between the C13 and the C14 atoms of morphine.

Dot-cloud models below, for example, help the researcher to visualize spatial relationships of the various atoms in the molecule. As still images, the models can be viewed from any angle. In general, programs used in the molecular modeling system are much shorter than most of the programs obtained from other sources. Adaptation of programs to run on in-house equipment has avoided the need for writing large numbers of extensive programs.

molecules, effects of substituents on conformation, and sources of fragments of specific information.

Visualizing and modifying. To draw a new molecular structure into the modeling system, the researcher runs the "Grafix" program at a CRT terminal. A digitizing tablet and an electronic stylus controlling a cursor are used to position atoms and bonds in two dimensions (x-y plane) on the screen.

The chemist selects basic organic atoms at the bottom of the screen (Grafix assumes carbon, unless the chemist indicates otherwise). Then, pointing to the "Move" function, the chemist changes the location of atoms. The bonds automatically stretch as necessary. The screen can become quite cluttered, but the computer is not concerned with the appearance of the drawing—only with what atoms are bonded to what other atoms.

Next, the "Z-modify" module is used to enter the z coordinate of one atom, a parameter necessary to begin the process of creating a 3-D structure. The z coordinate need not be a known dimension because its value simply determines the relative size of the model. Its position behind or in front of the x-y plane (minus or plus) is needed, too, to attain the proper chirality (the structure's left- and right-hand orientation).

The computer's first try at a 3-D representation of the rough 2-D structure drawn on the graphics screen can be a distorted version of a realizable molecular structure. Molecular mechanics analysis of the initial structure would indicate high total strain energy—so high that such a structure would be unlikely to exist in nature.

Therefore, the experimenter requests one of several molecular mechanics programs in the system to "minimize" the structure. That is, the computer will determine the configuration that has the lowest possible total strain energy—and which, thus, is the most likely to be realizable.

The molecular mechanics minimization programs request the necessary force constants from a system standard data base. But sometimes, a structure may require constants that are not yet in the file. In that case, a message is displayed on the CRT identifying those constants that the experimenter has to enter before minimization can proceed. New constants (after being checked for accuracy) are added automatically to the file; they become available to all users.

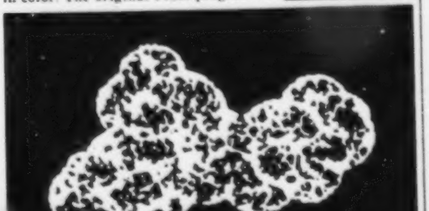
Molecular mechanics—*i.e.*, minimization—is an iterative process that can be quite demanding in CPU (central processing unit) time, but not nearly as demanding as molecular orbital analysis. When the chemist keys in the name of the desired minimization program, the system asks if the program is to be run in interactive, batch, or deferred mode.

In the interactive mode, the chemist can see the conformation changing from iteration to iteration on the screen. In the batch mode, the computer runs the program in its spare time, freeing the terminal for other work. The defer mode stacks batch jobs. Experimenters are encouraged to use the batch or the defer mode, since running in the interactive mode can interfere with other users who need quick responses.

As the program runs through each iteration, the computer produces a line of type giving iteration number and then average movement (sum of the movement of all atoms in the molecule divided by the number of atoms). The smaller the average movement, the smaller the reduction in total strain energy per iteration. When the change in energy between iterations is less than a given figure, minimization is deemed to be complete.

The minimization programs have several built-in automatic shutoffs that operate if the iterations are taking too much time (10 min. of CPU time per run is maximum) or are failing to converge. Minimization of the 41-atom morphine molecule, for example, requires about 5 min. of CPU time on the VAX-11/780 system. The minimized structure is stored in a new molecular descriptor file.

Graphics output. The "Pluto" and the "Mole9" programs are called up to display a stored molecule in any of several 3-D forms: stick, solid, surface, or space-filling in color. The original Pluto program re-



ceived with the Cambridge data base was extensively modified because it was not interactive, and because it did not support any CRT devices.

The user enters at the keyboard the desired viewing angle for any 3-D model. The structure always can be printed out in numerical form as well, and any CRT display can be recorded in hard copy on one of several plotters or cameras, or on video disk or video tape.

Among the special graphics programs written in the group, a program called "Newman" provides chemists with projections of molecular structures oriented along a specific bond. These projections are familiar pictorial tools; they are convenient for isolating small fragments of molecules.

The "Build" program permits experimenters to create analogs of a molecule by modifying segments of its structure on the CRT without having to redraw the entire molecule. For example, the methyl group bonded to nitrogen in the morphine molecule can be replaced by an allyl group—a small structure change, but a major change in biological activity.

Similarity searches. The Cambridge Crystal File is used to identify known molecules that contain fragments similar to structures under consideration. With the raw-data tapes are programs to facilitate searching for specific items of information. We have extensively rewritten each of the programs to achieve maximum speed (at the expense of machine independence).

The experimenter first creates a connectivity file by entering the atom types and the types of bonds that connect them in the fragment of interest. No spatial coordinates are known. The 28,000 molecules in the file then are searched by a program called "Connser" to identify those substances that contain the fragment somewhere in their structures.

Connser displays or prints out six-letter reference codes for all compounds that qualify. Depending on the size and conformation of the fragment of interest, this list may consist of 100 or more substances.

To narrow the list, the user can specify allowable ranges of bond lengths, bond angles, and dihedral angles in the matching fragments that are the most suitable to the structure under study. In addition, the "Retrieve" and the "Bibser" programs may be requested to retrieve geometries and bibliographic data on particular substances.

The search through all 28,000 molecules in the files, some of them quite large, can absorb a considerable amount of CPU time on the modeling computer. Taking advantage of special features in the architecture of the VAX-11/780 computer, we modified the three main search programs, Connser, Bibser, and Retrieve, to speed up program execution.

Connser and Bibser now run in a sixth and a tenth the time, respectively, required for the original programs; Retrieve runs in a thousandth of the original time. A typical similarity search—one that identifies, say, 100 qualifying compounds—takes a total of 5 min. of CPU time, in contrast with 2 to 3 hr for the programs as received.

Future of molecular modeling. We expect that the number of users will continue to grow, particularly as newly acquired programs extend the range of the molecular modeling capabilities. New programs, many of them suggested by experimenters, constantly are being reviewed as to their value in solving research problems better and/or faster.

The computational chemistry group has to evaluate the scientific validity of the techniques, and they must consider the programming time that would be invested in converting them to VAX Fortran code and in writing support software modules.

At present, the system can display structures with several thousand atoms, and it can do molecular-mechanics minimizations on molecules with as many as 250 atoms. Molecular-orbital analysis can handle as many as 100 atoms at a time, but it can handle no more than 10 or so for several of the most complex and time-consuming programs.

To support the growth of the system, we plan to acquire more computers in the coming years. By linking them through DECnet (Digital's network communications software), we will enable the computers to exchange data files and programs dynamically (and to balance loads).

In addition, as the first computer now can do, they all will be able to communicate with the Digital DECsystem-10 machines in the company's computer center. An array processor will be connected to one of the computers for faster execution of the more complex computations in molecular dynamics and for Monte Carlo simulations.

Among improvements in graphics capability, special-purpose circuitry will be developed to solve problems in electrostatics and in steric (bulk) interaction in real time.

As space-filling molecular structures are modified on a CRT screen, for example, the computer will display instant readouts of the changes in total strain-energy level. Another technique currently under development involves aligning two color screens to attain stereo mirror images of space-filling molecular models.

As the previous article stated, the modeling system is a true system, not just a monolithic program. The more practice we get in using the system, the better we are able to take advantage of the many aspects of the structural modeling.

The many scientists who use the system every day attest to the fact that we need the system for the rapid and efficient determination of new structures and for the predicting of properties of new materials on the basis of properties of related known compounds. □

THE AUTHOR

Dr. David A. Pensak is research supervisor, Central R&D Dept., E.I. du Pont de Nemours & Co., Wilmington, DE. He is a graduate of Harvard and Princeton universities. At DuPont, he specializes in molecular modeling by computer, interactive graphics, computer-assisted design of synthetic procedures, structure-activity correlation, and pattern recognition hardware and software.

Mr. **Brown**. Thank you very much, Dr. Pensak.

I would like to go ahead with the other witnesses this morning before we begin to question all of you.

Dr. Gilbert, would you like to proceed?

STATEMENT OF DR. FREEMAN GILBERT, PROFESSOR OF GEOPHYSICS, INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS, SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, SAN DIEGO, LA JOLLA, CA

Dr. **Gilbert**. Thank you very much, Chairman Brown.

I am grateful to have the opportunity to speak to you today. Rather than talk about the impact of the information age on science in general, I am going to stick to a very particular and very small branch of science, namely geophysics, and a subset of that, namely seismology. I am going to use just a few examples to show you how the geophysicist, how the seismologist, has reacted to the ability to acquire large volumes of information and process those volumes, and then I want to draw a few basic conclusions.

The first example that I am going to use is prospecting for oil. Even though we have a glut of petroleum today, I think that if you look far enough into the future, it is reasonable to believe that some day there will be another oil crisis, and some day we will be prospecting for oil even more strongly than we are at the present time.

It has come to be true that most of the petroleum fields that we have, and all of the deep ones—so deep that there isn't any seepage to the surface—have been discovered by indirect methods, methods primarily using geophysical prospecting, and in particular a form of geophysical prospecting that is very much like sonar or radar, except that it involves the propagation of sound waves in rock to form echo sounding.

The idea is to set off an explosion near the surface of the Earth and to record the echoes that return from the boundaries between different kinds of rock. By timing the arrivals of the echoes and by knowing something about the speed with which these pulses travel in the rocks, we can infer the depths of the boundaries, and then we can make cross-sectional maps of these boundaries and see places where there might be domes or pinchouts or faults. These are places where we might expect petroleum products to be concentrated. And then comes the real test with the drill.

Now, the problem that the geophysicist faces in doing this sort of prospecting is a problem of enormous scale. The regions to be prospected, whether on land or at sea, are quite large in area, and in order to get adequate coverage, you often need to use thousands of instruments at the surface to measure the arrival of the echoes. You need to use hundreds of explosions to cover the region well. Usually these traverses are along lines of echo soundings. You need many, many lines to cover a region. You can easily get yourself into the situation where you have 10 billion to 1 trillion samples of data for a particular prospect, and of course, many parts of the United States and the rest of the world have been covered by these prospects.

If you think of having on the order of 1,000 to 10,000 magnetic tapes for each prospect, you can see that the tape libraries of some of the larger petroleum companies are of gargantuan size, and in fact this represents one of the fundamental problems, the problem of management of a large library.

Let me give you an example of one of these cross sections that is prepared by the echo sounding method. The basic idea is very simple. I have a Vu-Graph that will illustrate it.

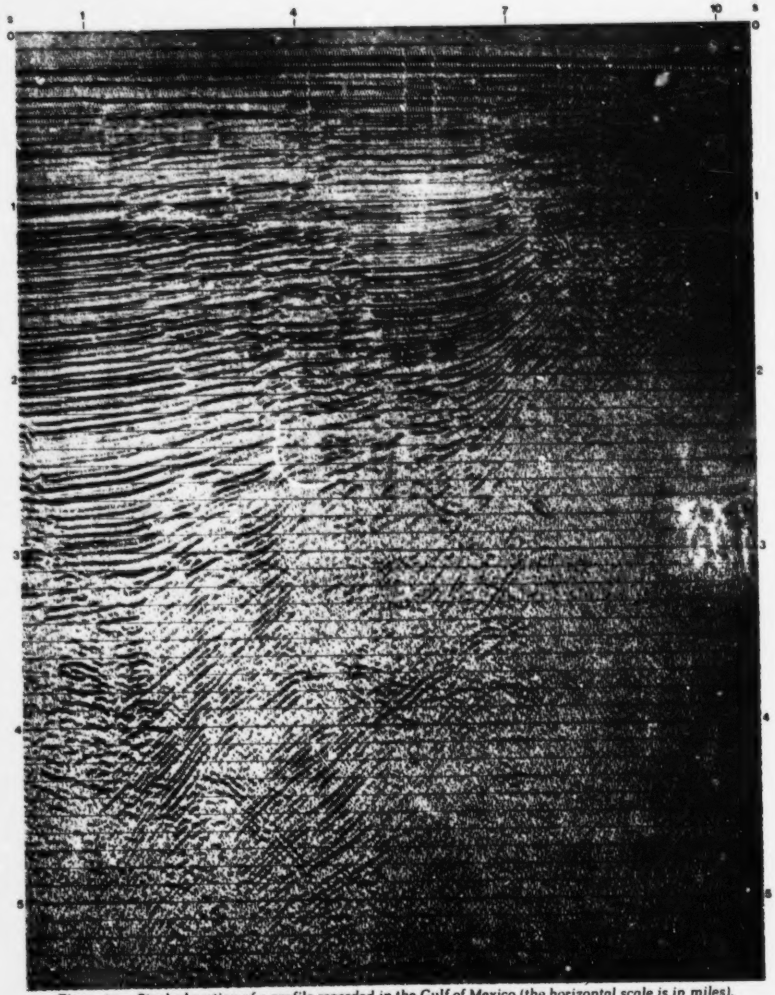


Figure 1a. *Stacked section of a profile recorded in the Gulf of Mexico (the horizontal scale is in miles). Note especially: (a) the faulting both above and to the side of the salt intrusion on the right, and (b) the complex region of crossing events between 4 and 5 seconds.*

Along the top we have distance in miles—1, 4, 7, to 10 miles—and down the left-hand side, on the vertical axis, we have times in seconds, 1 down through 5 seconds.

What you see is the superposition of the echo soundings from many hundreds of explosions and many thousands of recordings at the surface, and a variable contrast method is used to display the data. Computers are used to align these echoes and pick out the fact that there is an offset between the explosion and the recording instrument, and you can see many obvious visual line ups of the data.

In fact, what you are looking at is a prospect in the Gulf Coast of the United States. On the right-hand side, there is a soft dome; on the flanks of the soft dome you can see steeply dipping strata. Off to the left of the soft dome, you can see faults breaking the strata, and as you go deeper, you begin to run out of resolution. That can be modified by even more computer processing, but this is an example of a single traverse, many of which, hundreds of which, are needed to cover a region on the order of 10 miles by 10 miles square in the Gulf Coast.

Now, these computational problems that we are involved with saturate very large computer systems, I mean the state-of-the-art computer systems with disk farms and tape farms and large numbers of attached array processors. The problem is not only the speed of the computer but the ability to get data into and out of the computer. Imagine trying to get 10,000 reels of magnetic tape into and out of computer memory in order to do the kind of processing that leads to the cross-section that I just showed you.

So the question arises, what is the impact of such a huge volume of information on processing? There are six points that I would like to make.

The first is that managing a library of thousands of reels of magnetic tape is a challenging problem. Large data base management systems are used and frequently upgraded to handle the growing library. Nevertheless, some companies lose track of where a particular reel of tape out of hundreds of thousands is located.

The second point is that maintaining the integrity of the recorded magnetic tape is another challenge. Problems of printthrough, winding stress, and wrinkling require constant checking of the library. Some companies mount the tapes and spin them periodically to alleviate this problem. Other companies simply turn them a quarter turn every few months. Other companies simply buy the best possible magnetic tape and hope for the best.

The third point is that new algorithms for processing and interpreting the data may be retarded in implementation, particularly if they require more computer time. You can imagine the situation where, from the research laboratory of a particular company, a better method of constructing these cross sections is developed, a method that will extract more information. But the manager of the computer center, knowing that a certain volume of data must flow through it, may resist using that algorithm if it is going to take more time to implement it.

New hardware may not be accepted until its reliability has been thoroughly demonstrated. The first supercomputers of the kind that we talk about today were installed at the Federal weapons laboratories in 1976. It was 5 or 6 years thereafter before they began to be installed in the petroleum industry. I think that the reason is quite obvious: You don't put what somebody calls a supercomputer in the business of processing a large volume of data until its superiority has been thoroughly demonstrated.

The fifth point is that more accurate theories capable of extracting more information from the data may go unheeded in the press to process such large data volumes. The theories that are now used to process the data and to make the cross sections of the kind that I showed you are relatively elementary theories. They represent theories that are asymptotic in some sense—asymptotic in frequency of the waves being used, asymptotic in other ways. There are better theories. There is a more complete theory. But to implement that requires probably an order of magnitude more computational power.

Now, on the positive side, the resolution of finer detail in these cross sections leads to a correlation that is geological; that is to say, a trained geologist, knowing the character of the strata in a given region, can correlate those strata with the features on the cross section, so that when he sees a nearby cross section, he can go from the variable intensity plots like the one that I showed you and actually infer geological characteristics, whether it is shale, whether it is sandstone, whether it is limestone, whether it is salt. We now know that there are certain types of strata in which you don't drill, because if you do you will get a dry hole. Dry holes are incredibly expensive. And so the improvement of resolution is one way of circumventing—reducing, I should say—the frequency of dry holes.

Now, scientists are actually happy about the amount of data that they are able to acquire and process. They want to go farther. They want to gather more data. For example, rather than using explosions, for the past decade or so people have been using vibrators on the surface of the Earth to simulate explosions. With vibrators, you can vibrate not only vertically but also horizontally, something that is very difficult to do with explosives. So you can have a source that has three components rather than one that is desirable for certain technical reasons. It is also desirable to record three components of acceleration at the surface of the Earth rather than one. Now, if you do both of those things, you have nine times as much data, and you have, in addition to nine times as much data, a greater richness of information that requires more than nine times as much computer time to process.

It is also desirable to make areal traverses rather than the usual linear kind that lead to the linear cross sections that I showed you. In an areal traverse, you would set out your recording instruments in an array, a two-dimensional array, for each explosion or each vibrator source. Now, if you do that, you have a data volume proportional to the product of the number of sources and the number of receivers, rather than a sum, and so if you have 100 sources and 1,000 receivers, you can see that you have an enormous quantity of data. You have so much data that you don't know how to manage it at the present time. Even if you could manage it at the present time, you don't have computers that would allow such volumes of data to go in and out of the computer. Many people talk about using computers because of their great speed, but you cannot take advantage of that speed if you cannot get large volumes of data in and out of the computer memory, and that is a problem when you are gathering enormous quantities of data in a prospecting environment.

So, to sum up what it is that the petroleum geologist, the prospecting geophysicist, has accomplished, I think that you could say that the benefits are enormous from the revolutions in electronics and computing and actually in other fields as well—making vehicles that are able to stand up to the rigors of prospecting in very adverse situations.

I think that the attitude is one of looking forward to improvements in the various methods that are being used. For example, many people now would like to find a method—and some think it is possible—not to look at the geological strata and then drill and see if there is any oil there, but to try to detect the presence of petroleum directly through other methods than seismic reflection profiling.

I think that the press to do more from the prospecting industry represents a feedback from science to the informational age, and I believe that it is a tribute to the ever-forward-looking attitude that young people have when they enter a profession. They take for granted what is there. They want to do more; they want to do better. They are pushing hard on the frontiers of those technologies that will allow them to acquire the 10 or 100 times as much data, do the computing, come out with three-dimensional profiles instead of the two-dimensional profiles that I showed you. So I believe that this is a healthy situation, that we will continue to have a desirable interchange between the acquisition of information and the advancement of this particular branch of science.

Now, there is a rather strong alliance between academic institutions in geophysics and industrial companies, research laboratories, in the petroleum and mining industry, and there is one spinoff from the petroleum prospecting industry that I would like to mention briefly because testimony has been presented in the past years about it. It is the Consortium for Continental Reflection Profiling—COCORP for short—located at Cornell University and originated by Prof. Jack Oliver. Using mostly techniques developed in the petroleum industry, COCORP has been able to resolve the crustal structure of some very important regions in the United States; for example, the Wind River Thrust in Wyoming, part of the Rocky Mountain overthrust belt, and the Brevard Zone in the southern Appalachians, a section of great geological interest that had 18 different theories on its origin before COCORP was able to allow geologists to look beneath the surface and see exactly what was there.

Now, another outgrowth of this improved methodology in prospecting and also from the field of medicine is a program to study the continental lithosphere. The continental lithosphere is about the outer 100 kilometers, outer 60 miles, of the Earth's crust, and there is tremendous interest in the U.S. academic community to prospect the continental lithosphere to see what is there and then to speculate on how it got there. This does itself represent a large data-gathering series of experiments and data-processing requirements thereafter. It is not uncommon, in these projected experi-

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ments, to think of data bases on the order of trillions of bytes of information.

Once again, just like in prospecting, the ability to manage such large volumes, even to manage the experiments themselves, is one that requires not only the fastest computers but those that have the ability to have large volumes of data go in and out of computer memory.

Another program that the U.S. university group is very interested in is the establishment of a new digital, global, seismic network so that we can understand, for example, the structure of earthquake sources much better than we do now.

Quite a lot of progress has been made in the past decade in the understanding of earthquake sources, and there are many reasons—mitigating earthquake hazards being one of them—for having an even better understanding of how earthquakes happen, how ruptures are initiated, and so forth. If it is possible, as we hope, to transmit the data from the proposed new global network in real time to one or more centers, we might be able to give early warning—that is, very credible early warning—about, for example, the generation of tsunamis.

Most tsunamis are caused by earthquakes near the seashore or beneath the sea bottom. There are several factors about the earthquake that cause a tsunami, make the sea floor flex and generate the giant wave. These include the magnitude, depth, location, and mechanism of the earthquake, and the shape of the ocean basin across which the tsunami propagates. Tsunamis propagate very quickly, so if we could obtain real-time data within an hour or so after the earthquake, we could calculate the magnitude, depth, location, and mechanism, whether it is a thrust, whether it is a horizontal slip, and, in a matter of 2 hours, a warning could be issued or not about the danger from a tsunami.

Tsunamis travel across the deep sea very quickly. They travel at a speed of about 200 meters per second, which is about 450 miles per hour. So, with a 2-hour warning, you could warn distant shorelines of the danger. Parenthetically, I should say that the very large earthquake in Chile in 1960 created a tsunami that devastated the harbor in Hilo, HA, and beached fishing boats on the coast of Japan. In the case of Japan, it took many hours for the tsunami to propagate, and had the fishermen been able to have a warning within 2 hours, they could have saved their vessels. So I think that that is one example of why a global network would be of societal value, and it illustrates the extent to which that societal value comes from fundamental research on studying earthquake source mechanisms.

One other aspect of studying earthquake source mechanisms is the problem of reduction of earthquake hazards, the mitigation of earthquake effects, or, as some people are brave enough to say, earthquake prediction. Whether earthquakes can be predicted, I don't know. There are many of my colleagues who say "I don't know," also, but there are a few of us who are optimistic that at least some earthquakes in some places can be predicted.

One of those places is in Parkfield, CA, which is about 150 miles northwest of Los Angeles on the San Andreas fault on the western side of the San Joaquin Valley. In 1966, there was a moderate magnitude 6 earthquake in Parkfield. The population there is sparse; the damage was not great—I don't believe there was loss of life—and very little property damage. Now, it turns out, looking at the historical record and the early instrumental record, that very similar earthquakes occurred in 1857, 1881, 1901, 1922, and 1934. With the exception of the 1934 earthquake, these other earthquakes have an interval of about 21.9 years.

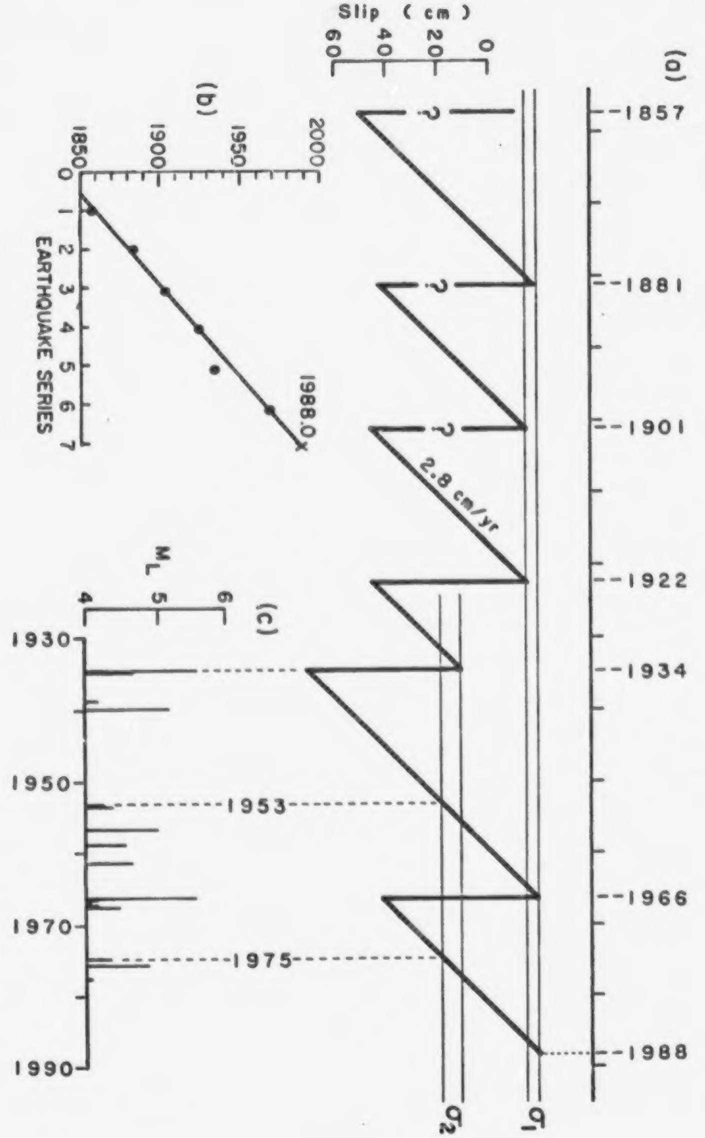

FIGURE 2

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Looking at the records of the earthquakes in 1922, 1934, and 1966, they are very similar. They are almost identical. The main shock and aftershock sequences look very much the same, and it appears that what happens is that there is a section of the San Andreas fault that periodically ruptures in very nearly the same way. Let me show you what I mean by that.

The theory is that the San Andreas fault, representing the primary boundary between the continental North American crustal plate and the ocean——

Mr. **Brown.** I think you have that upside down, don't you?

Dr. **Gilbert.** Let me see how I want to put this. I think I will put it that way.

The San Andreas fault, representing the boundary of the North Pacific plate and the North American plate, is moving at a rate of about 3½ centimeters a year, about 1½ inches a year, and there are certain sections of the San Andreas fault that creep. There is a section in the central valley of California that simply creeps, that has no earthquakes on it.

There is a section south of Parkfield that doesn't creep at all, and every century or two—we are not exactly sure how frequently—it has a great earthquake. Parkfield is sort of a transition zone. It appears that every 22 years or so, after you have accumulated a certain amount of slip, on the order of 60 or 70 centimeters, you have an earthquake to relieve that slip. The strain builds up, you have another earthquake, and so forth.

Apparently, in 1934, there was something of an early episode, but you can see down in the lower left-hand corner, you can make a graph of calendar time versus a numbering of earthquakes, and they fall very nicely on a straight line, with the exception of 1934, which was early. But even then, the interval between the earthquake in 1922 and 1966 is twice the usual interval; it is 44 years instead of 22. So the hypothesis to be tested by scientists at the Geological Survey is that if you extrapolate that straight line, the next earthquake is due in January 1988, and if you take into account the fact that the line is not a perfect fit to the data, so that you can wiggle the line a little bit and get a range of times when the next earthquake should occur, if the hypothesis is correct, it should occur between 1983 and 1993.

Well, we are already in that region of time. So what has happened is that this area around Parkfield has been very heavily instrumented with virtually every kind of monitoring instrument we can think of, instruments that measure acceleration, creep, change in volume, magnetometers to monitor changes in the magnetic field. This represents information, large volumes of information flowing back to the U.S. Geological Survey headquarters in Menlo Park, CA, where immediate online processing is done whenever microearthquakes occur.

Now, the interesting thing about the 1988 forecast is this: All the earthquakes starting in 1857 appear to have started in the northwestern part of the fault, ruptured to the Southwest, and stopped, and the shady zone shows you where they have ruptured, except that in 1857, it appears that this small little wrinkle in the San Andreas fault was overloaded and was the place where the great Fort Tejon earthquake occurred. That earthquake had 3.5 meters

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of slip. That is about 12 feet, from one side of the fault to the other. Now, as I said, the San Andreas Fault moves at a rate of about 3½ centimeters per year, or actually the two plates move at that rate, so that slip in over 100 years has been recovered, and many people believe it is ready to slip another 3.5 meters sometime soon. So one of the speculations about the forecasted 1988 earthquake is that it could act like another trigger like the 1857 earthquake did, and then you could get another 3½-meter earthquake going down toward Los Angeles.

So there are two speculations there that are being tested, two hypotheses. One is that these earthquakes occur on a regular basis and that the next one is due in January 1988 or maybe as late as 1993. I don't think that it is fair to say that my colleagues are hoping for an earthquake, but they are certainly anticipating one because of all the instrumentation they have in that region.

Second, if it is true that the slip of the 1857 earthquake has been recovered, it is a testable hypothesis that in 1988, or 1993, or thereabouts, we will get another Fort Tejon-like, 3½-meter jump in the Earth.

This is only one place where earthquakes occur frequently enough so that a human's lifetime, or his plus his parents' and his grandparents' lifetimes, are enough to say, "Oh, yes, I remember that earthquake and the one before that and the one before that." There are other places where repeat times are on the order of 100 years. There are other places where it might be 200 years, and there are places, when you look through the 2,000-year-old Chinese catalog, where the repeat time is perhaps 500 years.

So you can imagine the effort that it would take to monitor all of the active faults in the world, especially those that could damage the works of man or threaten human life if you were going to try to predict these cycles if, indeed, they all have cycles.

So this is an example of gathering an enormous amount of information over a very long period of time, because if these scientists are correct and there is an earthquake in 1988, there will have to be a renewed effort to increase the monitoring so that the next earthquake, in the next century, will be even more anticipated; some would say predicted.

So once again, you have the problem of large volumes of data, the need for very high-speed computers to evaluate the models that are used to explain the data, and computers with enormous input/output band widths to enable you to process all of the data.

And so that remark leads to the few conclusions that I have. The first is that the volume of data to be acquired and processed is very large. This leads to the need for good management of the data libraries, the need for very large-scale computers, including input/output of large data sets, and an evermore quantitative approach to the problems of inference.

The second point is that the modeling calculations are daunting even on today's fastest computers. It is difficult even now to do realistic three-dimensional calculations.

The third point is that improved theoretical understanding to derive more information about the Earth and its processes is stimulated by the quality and size of the data set and by the improved availability of the best computing resources. I should say parenthetically at this point that the recent program of the National Science Foundation to make supercomputer facilities available to the university community is a very definite first step in the right direction.

The fourth point is that research tends to be done by teams of scientists, often from several institutions, including industrial, academic, and governmental members. However, the seminal, creative ideas are individually conceived. There is always going to be probably a bright young person who will say, "Look at this correlation; that gives me an idea"—gives me an idea, not us.

Thank you very much.

[The prepared statement of Dr. Gilbert follows:]

Science Policy Task Force

Hearings on

Impact of the Information Age on Science
September 11, 1985

Written Statement of Proposed Testimony

Freeman Gilbert
Professor of Geophysics
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California 92093

Chairman Brown, members of Congress, distinguished guests, ladies and gentlemen, for the next few minutes I shall address you about the impact of the information age on science. Because of the very great diversity of the general subject I shall deal almost exclusively with the field of Seismology. The few points that I want to make will be illustrated by examples, and from them I plan to draw general conclusions.

Prospecting for Oil

The first example is the exploration for petroleum - gas and oil. Most of the world's major oil fields, and all of the deep ones, were discovered by geophysical exploration. Today, the most used form of geophysical exploration is seismic reflection profiling - a form of echo sounding. By timing the arrival of echos from small, surficial explosions one can map deep boundaries between different types of rock. Domes within boundaries and pinchouts between them are candidates for petroleum reservoirs. They are tested by drilling. In the echo sounding method instruments at the Earth's surface, called geophones, measure small fluctuations in ground acceleration as the echos from the initial explosion return to the surface. The measurements are made digitally at 128 to 256 samples per second and are recorded on magnetic tape. Each record is about 4 to 5 sec long. For each explosion there may be as many as 1024 geophones. For each linear traverse of a region there can be several hundred explosions. To cover a region thoroughly many linear traverses are needed. A thoroughly prospected region may require 10^{10} to 10^{12} samples. Up to 10,000 reels of magnetic tape may be needed to store the samples. These data are processed by large computers to align the echos and suppress the noise. Inferred geological cross sections are prepared and analyzed by petroleum geologists. The processing goes on continuously and saturates very large computer systems that have high speed, attached, array processors. What impact does the huge volume of information have on the science of prospecting?

1. Managing a library of thousands of reels of magnetic tape is a challenging problem. Large, database management systems are used and frequently upgraded to handle the growing library.
2. Maintaining the integrity of the recorded magnetic tape is another challenge. Problems of print-through, winding stress, and wrinkling require constant checking of the library.
3. New algorithms for processing and interpreting the data may be retarded in implementation, particularly if they require more computer time.
4. New hardware may not be accepted until its reliability has been thoroughly demonstrated. Innovation may be slowed.
5. More accurate theories, capable of extracting more information from the data, may go unheeded in the press to process the everpresent data volume.
6. On the positive side, resolution of finer detail in the inferred geological cross sections leads to correlation between "character" on the cross sections and known geological strata. This, in turn, reduces the frequency of dry holes.

Stimulated by the success of the echo sounding method, seismic reflection profiling, scientists want to improve it and to implement variations of it. One can emulate a surficial explosion by applying a vibrating force to the Earth's surface, and this has been done with great success. Now, it is desirable to apply three components of force, one vertical and two horizontal. Also it is desirable to record three components of acceleration rather than only the vertical. Together, these represent increasing the number of samples by a factor of nine. It is desirable to make areal traverses rather than linear traverses of a region. This leads to a data volume proportional to the product rather than the sum of geophones and sources. Clearly such a data volume is unmanageable at the present time. One needs other, very reliable recording media than conventional magnetic tape. One needs computers with huge input/output capacities as well as computers with very high computational speeds.

The petroleum geologist has benefited enormously from the informational impact on his science. Some are eager to improve existing methods while others believe that new methods must be developed, for example, to detect directly the presence of petroleum. Although some difficulties have arisen and been identified, it is quite clear that the informational age has been a positive stimulant to the prospector. He is eager to increase the informational throughput by a few orders of magnitude. His desires represent a feedback from his science to the information age.

COCORP

One of the recent academic beneficiaries of developments in reflection seismic profiling is the Consortium for Continental Reflection Profiling (COCORP) located at Cornell University. Originated by Professor

Jack Oliver, COCORP has been very successful in resolving the geological structure of the deep crust in several sites in this country. COCORP is sponsored by the National Science Foundation and represents a very good example of technology sharing between academic and industrial institutions.

PASSCAL

Another outgrowth of the improved methodology of prospecting is the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL). PASSCAL is one of the research projects of the Incorporated Research Institutions for Seismology, inc. (IRIS), a consortium of about 50 U.S. universities. PASSCAL seeks to mount several regional experiments, each involving about 1,000 three component seismographs and a large number of surficial explosions. The objective is to determine images of the continental lithosphere, the outermost 100 km or so of the Earth. The traverses will be areal rather than linear so that the digital data produced by one large regional experiment will be several Terrabytes (1 Tb = 10^{12} bytes). The analysis of the data will be based on prospecting methods and on tomographic image reconstruction techniques, successfully adapted from medical applications to seismology. In the PASSCAL experiments the largest problem is the management of the huge datasets. This is closely followed by the need for very powerful computing facilities; for example, one of the recently funded NSF supercomputer centers. IRIS, and through it PASSCAL, is funded primarily by NSF. The PASSCAL program is expected to get underway in FY 86.

Another program being conducted by IRIS, inc. is the development of a new, global network of digital seismographs. The goal is to have about 100 stations around the world, each sending its data to collection centers for early analysis and distribution.

Global Seismic Network

In the long run it is very desirable to have the data transmitted by satellite or land line without delay. This is important for a number of reasons.

For example, tsunamis cause extensive damage. It is widely known that most, if not all, large tsunamis are caused by the flexure of the bottom of the sea associated with large earthquakes. Many factors determine the size of a tsunami. These include the magnitude, depth, location and mechanism of the earthquake and the shape of the ocean basin across which the tsunami propagates. If the new, global seismic network (GSN) transmits all data in real time to one or more collection and computing centers, it would be about two hours after the earthquake before enough data had been received to complete the initial computations. By that time the earthquake's magnitude, depth, location and mechanism (direction of slip) would be known. If the location is at sea or near the seashore, the depth is shallow, the magnitude is large and the mechanism is a thrust then a tsunami is likely. In fact, today scientists can calculate how a given earthquake would initiate a tsunami, and how the tsunami would propagate across a particular ocean basin. Thus, by using real time GSN data and the most powerful computers scientists could issue a tsunami warning in a little more than two hours after the causative earthquake. In the deep sea tsunamis travel at a speed of about 200 m. per s. (450 mph) so a warning two hours after initiation would serve to protect distant coastlines. Early warning for local coastlines is a very much more difficult problem.

The seismological study of earthquake source mechanisms may lead to a better understanding of the processes that occur when an earthquake fault ruptures.

The Parkfield Vigil

As our ability to learn about earthquake sources has improved and as our knowledge about them has increased several people have been addressing the problem of whether some earthquakes can be predicted. Even if successful earthquake prediction proves to be an elusive goal, our improved understanding about earthquake sources and related strong ground motion should lead to a reduction in earthquake hazards and a mitigation of earthquake effects. As an example of the kind of study being undertaken I shall describe a vigil now being kept in Parkfield, California, a research project sponsored by the U.S. Geological Survey.

In 1966 there was a moderate (magnitude 6) earthquake in Parkfield, California. It was very similar in several respects to another Parkfield earthquake in 1934. In fact, the entire sequences of main shock and aftershocks were remarkably similar. [W. H. Bakun and A. G. Lindh, 16 August 1985, The Parkfield, California, Earthquake Prediction Experiment, Science, pp. 619-624, volume 229, number 4714] Further research shows that since 1857 there have been five moderate earthquakes with similar features near Parkfield on the San Andreas Fault. The interval between successive earthquakes is nearly constant averaging 21 to 22 years. If the 1966 earthquake is followed by one at that interval it will occur in January 1988. That is a "big if" and scientists are mounting a vigil, a long term monitoring experiment to record as much data as they can in hopes of learning as much as possible about the anticipated earthquake sequence. Instrumentation includes seismometers, two-color laser strain monitors, tiltmeters, dilatometers, creepmeters and magnetometers. While the volume of data will not be as large as some that I have mentioned, correctly modeling the next earthquake, presuming that it is well recorded and does occur as anticipated, could be a demanding computational task. However, a better understanding of the characteristic Parkfield sequence could lead to improved models of earthquake sequences elsewhere. These include large and great earthquakes along the world's plate boundaries. Finally the 1857 Parkfield earthquake appears to have broken through the southeast end of the usual rupture zone and to have triggered the great Fort Tejon earthquake of 1857. Southeast of Cholame that earthquake caused slip of about 3.5 m. The slip rate between the N. American and Pacific plates is about 3.5 cm per year, so the 3.5 m slip of 1857 has been recovered. Thus, it is a tenable speculation that the next Parkfield earthquake, like the one in 1857, will break through the usual rupture zone and trigger another great earthquake. In any case the vigil continues. Data are being collected and analyzed. Models are being hypothesized and tested. Within the next decade we should have a very much improved understanding of the earthquake rupture process.

Conclusions

All of the examples that I have discussed have a few factors in common.

1. The volume of data to be acquired and processed is very large. This leads to the need for good management of the data libraries,

the need for very large scale computers, including input/output of large datasets, and an ever more quantitative approach to the problems of inference.

2. The modeling calculations are daunting even on today's fastest supercomputers.

3. Improved theoretical understanding, to derive more information about the Earth and its processes, is stimulated by the quality and size of the dataset and by the improved availability of the best computing resources.

4. Research tends to be done by teams of scientists, often from several institutions and including industrial, academic and governmental members. However, the seminal, creative ideas are individually conceived.

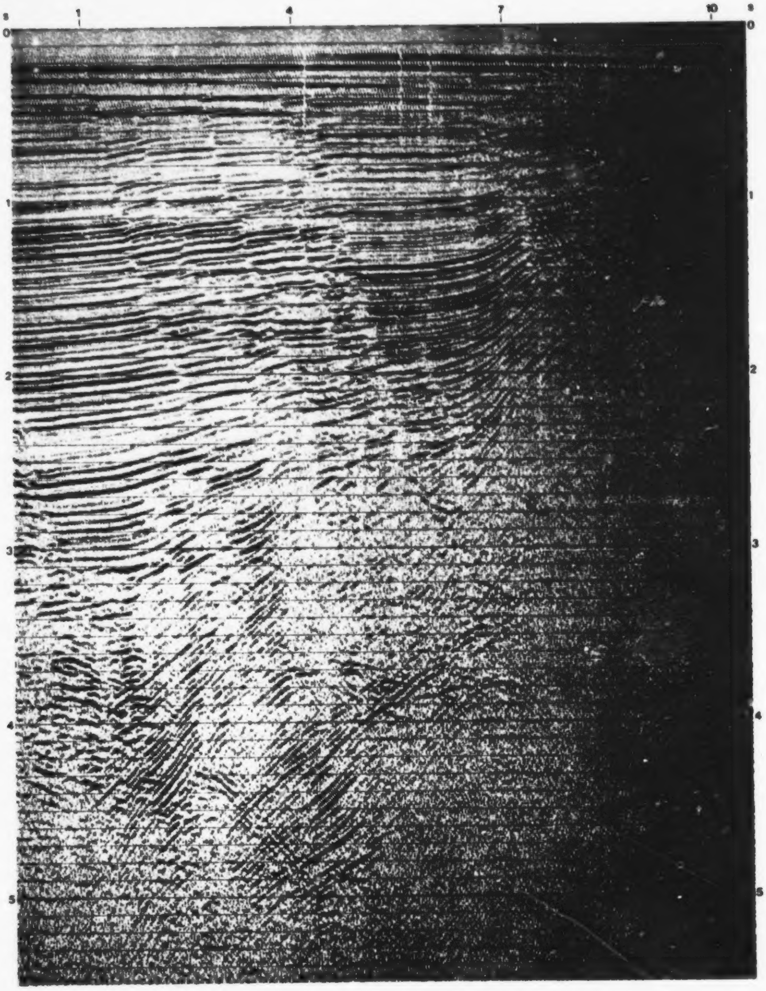

Figure 1. (Society of Exploration Geophysics) Stacked section of a profile recorded in the Gulf of Mexico (the horizontal scale is in miles). Note especially (a) the faulting both above and to the side of the salt intrusion on the right, and (b) the complex region of crossing events between 4 and 5 seconds.

PASSCAL

Program for Array Seismic Studies of the Continental Lithosphere

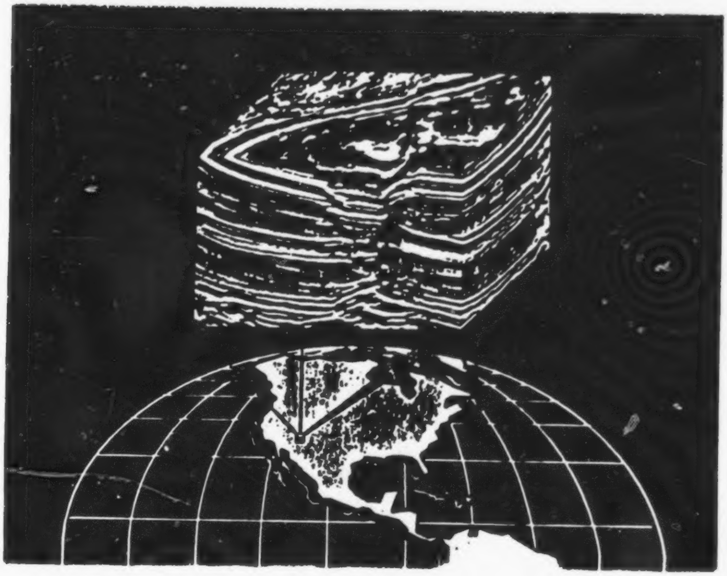

Figure 2. PASSCAL experiments are designed to construct three dimensional images of the continental lithosphere.

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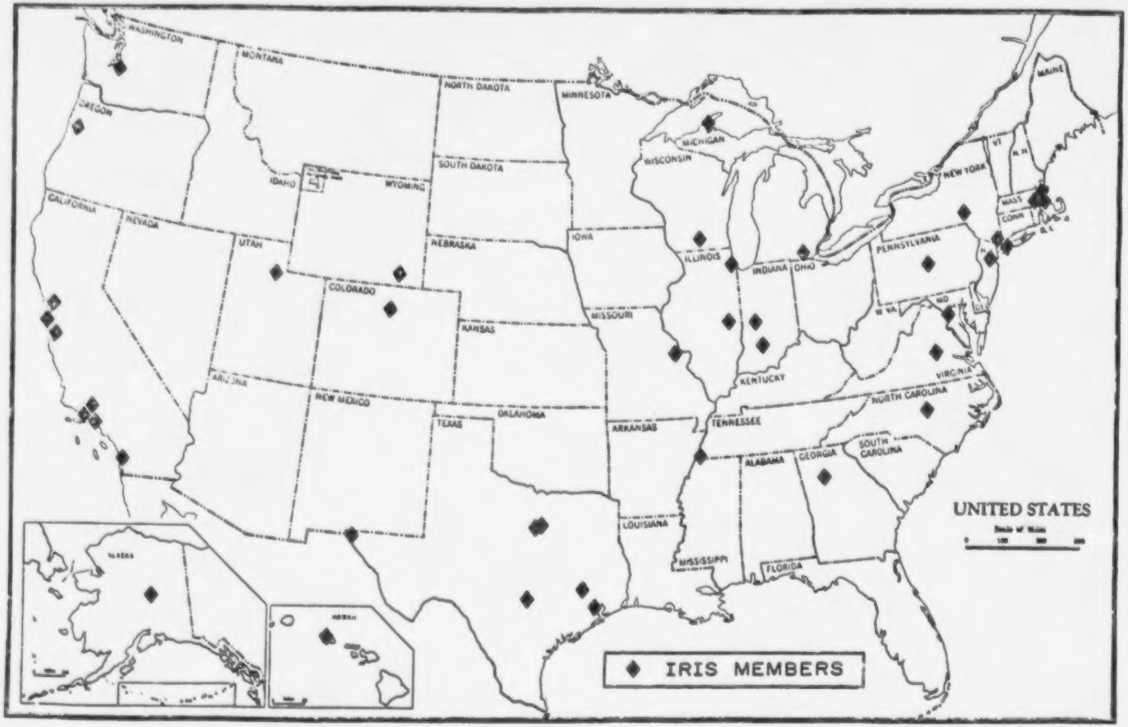
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Scale of Miles
◆ IRIS MEMBERS

Figure 3. Map of IRIS members as of early 1985.

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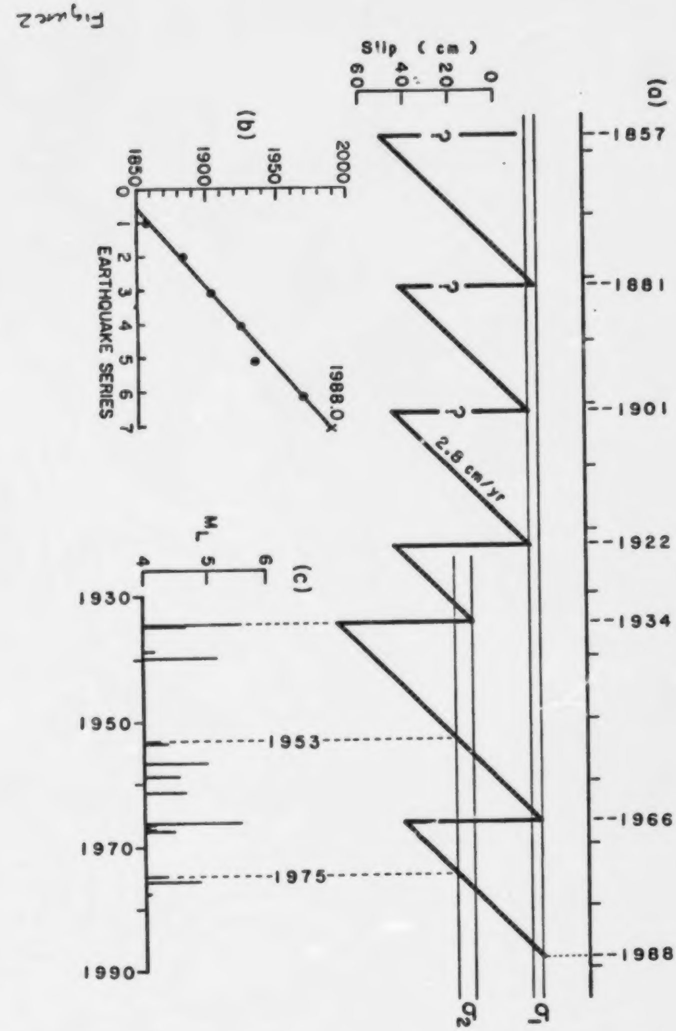
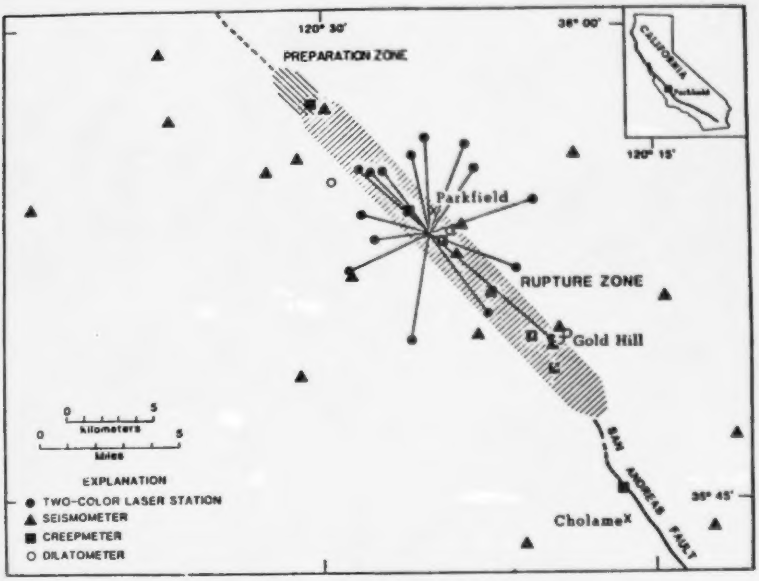


Figure 4. Figure 2 (with permission) of Bakun and Lindh, 1985. (a) The Parkfield recurrence model. σ_1 represents the failure stress of the fault. Most characteristic earthquakes occur at σ_1; the 1934 shock occurred at σ_2. Constant 2.8 cm/yr loading rate and 60 cm coseismic slip for the Parkfield earthquake sequences in 1881, 1901, 1922 and 1934 and 1966 are assumed.

(b) Series of earthquake sequence at Parkfield since 1850. Line is the linear regression of the time of the sequence obtained without the 1934 sequence. The anticipated time of the seventh, i.e., the next, Parkfield sequence for the two regressions is January 1988.

(c) $M_L > 4$ shocks since 1930 have tended to occur when the stress exceeds σ_2.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■ CREEPMETER
○ DILATOMETER
SAN ANDREAS FAULT
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Figure 5. Figure 4 (with permission) of Bakun and Lindh, 1985.

Mr. **Brown**. Thank you, Dr. Gilbert. Your testimony is extremely useful and, of course, provocative to those of us from California who are worried about the rest of the United States possibly sinking off into the Atlantic Ocean some day. [Laughter.]

Mr. **Lujan**. But, I must say, you have taken all the romance out of prospecting. There is no room for the little old guy coming out of the mountains on the burro. Maybe we will have an R2D2 walking out of——

Dr. **Gilbert**. I am afraid you are right, that the late 20th century, early 21st century burro will probably have pushbutton control.

Mr. **Brown**. All right, Dr. Hubbard, you are next.

STATEMENT OF DR. JOHN H. HUBBARD, PROFESSOR OF MATHEMATICS, CORNELL UNIVERSITY, ITHACA, NY

Dr. **Hubbard**. Thank you very much, Mr. Brown. I wish to thank the committee for the opportunity to testify.

I am going to speak about the applications of computers to mathematics, both to mathematical research and to mathematical teaching, because I think they are very closely linked.

Traditionally, people have complained about mathematics, and they have complained that it is utterly unable to describe the really interesting situations in nature. For the theory of gravity, it was able to describe two-body problems but unable to describe three. For chemistry, it was able to describe the hydrogen atom, but it was unable to describe even helium, never mind anything more complicated. But computers have changed that. Nowadays, it is reasonable to hope that we can describe interesting, realistic phenomena directly from the fundamental equations of nature. It is a very exciting time to be in, that finally mathematics can in fact succeed in describing nature.

All the systems we have heard about this morning and many more, some of which I will mention, are in fact fundamentally very similar. The mathematics that describes them is very similar, and that is because it is the mathematics of differential equations.

A differential equation is a way of modeling a real system essentially by telling you not what it is actually going to do as a function of time but how, if it ever reaches a certain state, it will then be pushed. It is the gradient side of Newton which really started the scientific age, that this is the correct way of describing nature; that you should never think of actually understanding the evolution of a system immediately. You should always try to understand it sort of infinitesimally. If it ever gets there, what is it going to do next?

Every single major law of nature is in fact a differential equation. And that is why the techniques both for modeling molecules and for modeling the deep structure of the Earth and many others—those used for modeling the flow of air around an airplane wing—are all basically the same technique.

Now, there is a serious problem. These equations have been known for 200 years in some cases, 60 years in others. The fundamental equations, the law of gravity, Schrödinger's equation in quantum mechanics, the Navier-Stokes' equation in fluid mechanics are all perfectly classical, but they are extremely intractable by

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the classical methods of analysis of paper and pencil. You cannot in fact solve them in the sense in which people in school solve problems.

The first person who really understood this was the great French mathematician Poincaré, who was attracted to the problem when a prize was given by the King of Sweden in 1885. The King of Sweden put a prize on trying to solve the three-body problem, trying to actually understand, just give formulas, for how three bodies would move under gravity.

Poincaré won the prize, but he won the prize not by solving the problem. He proved that it was unsolvable by the methods which people were then looking at. I want to show you some pictures of the extraordinary complexity that he glimpsed at that time in this particular problem.

I have two pictures which were produced by investigations of that particular problem. Nowadays, we understand them very well, but at the time—well, at the time, nobody understood them at all.

There is one picture, and a much more entertaining one is a small blowup of this one, there. Now, this is what Poincaré—of course, he did not have computers, but he had a glimpse that something like this was going to occur when you tried to understand the three-body problem, that there was going to be a combination of order represented by the curves which you can see in here, and chaos, which is the regions in which things bounce around.

This insight that he had has turned out to be probably the most important theoretical tool in the investigation of differential equations. I will have more pictures later.

Largely as a result of this perceived complexity, the field of differential equations, which had traditionally been the central topic of mathematics for 200 years, somewhat fell from favor. There were still great men working in it, but other subjects attracted most of the talent, and this had a very unfortunate effect on the interactions between mathematicians and members of other sciences. Well, I think we can fairly say that this has stopped, that the interactions are now much closer again than they used to be, and that the credit goes largely to the computer.

I want to give you now an example that I have been personally involved in of how the computer can help one to understand something quite specific. The example that I want to talk about is Newton's method. Newton's method is a tool for solving equations, just solving equations. You want to solve x cubed plus $3x$ minus 1 equals zero or something.

Well, you know, for quadratic equations, we probably all learned to minus B plus or minus the square root of B squared minus 4AC over 2A. But that is sort of more or less the end of formulas for solving equations. After quadratic equations, you don't have formulas. You have to do something else, and Newton's method is an iterative scheme for solving equations.

You start with a guess, and it is a scheme. You feed it into the computation, and the computation gives you an improved guess which you feed back into the computation, and it comes out a further improved guess. At least you might hope so. There is a theorem which guarantees that if you start with a sufficiently good guess, then this will in fact improve it. But if you don't, then you might converge to some altogether different solution or not converge at all.

Now, this is important. It is not just a mathematical abstraction. Solving equations is something that everybody has to do constantly. In all of the problems that either of the two previous witnesses have talked about, Newton's method is probably used at many places in every single sense. In some sense, it is like the nuts and bolts of engineering. You don't really—it is not perhaps so fashionable to really study nuts and bolts, but improving them would really be important.

Well, in 1976, when I was teaching, I decided that I would try to teach Newton's method to my students. Those were the days of programmable calculators, and Newton's method happens to be one of the few things that are sufficiently simple that you can in fact program them on a programmable calculator. And so I taught it. But you have to teach two things. You have to teach what algorithm to repeat over and over in order to improve the guess, and in principle, you ought to also tell them how to give them a good initial guess. But the more I thought about it, the more I realized that I had not the faintest idea how to give a good initial guess. So I went and consulted the literature and my colleagues, and I discovered that nobody had the slightest idea how to give a good initial guess. So I went to the computer and performed the following experiment: Take an array of cases, check to which route the method will lead you, starting from that guess, and color the plane according to which route you converge to.

Now, I want to show you the pictures which actually came up as a result of this. Here is the first one. There are three routes for this equation, so there are three colors that you can color the plane in, and, well, this is the pattern that you get.

Here is a blowup of what is happening in the center. No, it isn't. This is another picture that you can get in that problem. Here is another. There is another. All of these just correspond to taking some particular third degree polynomial and coloring various initial guesses according to which route you are going to converge to.

You should realize it is hard to imagine a simpler program than the one that produced this. The program is perhaps 10 lines long.

How about that, now? Or this? Just look at the extraordinary intricacies. The yellow is the region where you don't converge at all. There is another one, colored in a different way. And that is a different problem.

Well, just think. Newton's method has been used day in, day out, by virtually every applied scientist for hundreds of years. Nobody had, 10 years ago, the faintest idea of what it actually did. It was used sort of on trust. Now, as a result of these experiments, I think we will have a complete description of what Newton's method actually does.

I anticipate that there will be, at the end of the year, a paper which was begun 100 years ago by Cayley. He announced he solved what happened to the second-degree equation, and he announced that he would, in a soon-forthcoming publication, give the corresponding description for the third-degree equation. This occurred, incidentally, in the first publication of the first American mathematical journal, the American Journal of Mathematics, in 1885, in

September exactly. I anticipate that we are finally going to complete his work.

There are two things that I want to talk about. The first—that I want to mention about this particular problem, but about all problems of that nature. The first is, of course, you have to compute. Our previous speakers have spoken a lot about the massive amount of computation that is necessary. That is not the case with this, which is a model problem, but of course it becomes the case when you switch to more realistic situations.

After you have performed these computations, you have to display your data. People talk about a picture as worth a 1,000 words. That is completely wrong. The pictures that we saw here are worth about 200,000 words, in the sense that it would take about a 50-page book to tabulate the information that there was in one of those pictures.

Graphics are absolutely essential. The human mind is designed for processing graphic information, not for processing tabulated information. You have to have graphic output from your computer. A computer without a good graphics terminal is next to useless.

Another thing is that computer calculations are prone to error. You have to be able to deal with the error. What are you in fact going to do? You look at these pictures. You analyze them. How can you be sure that what you are seeing is the reality, or the error, that you are not seeing some artifact of the computation?

The job of mathematicians is still, as it always has been, to extract the information from these pictures to form from it some sort of conceptual understanding and to try to prove that what they are seeing is really there. The computer has not replaced the mathematician.

Next I want to talk about teaching. Observe that this particular line of research, which has turned out to be very important, grew immediately out of a course in first-year calculus. Actually, the entire mathematical curriculum is filled with avenues off the side which have never been investigated because nobody knew how, and which the computer is now opening to investigation. It is not that they were not important. They were perfectly important. It is simply that we didn't know how to solve the problems, and the mathematical curriculum is a very, very thin trail, delicately set among all the precipices of just our ignorance and our inability.

Now we can really hope to push out and to try to understand these interesting and important phenomena which previously have been ignored because of our incapacity. We must take the students along for the trip. If we teach our students only the paper-and-pencil techniques that are part of the traditional curriculum, they will not be properly trained.

The problems which can be solved by paper and pencil are atypical. It is basically misleading to try to give the classical treatment, because the problems that you treat are in fact not the right ones. They do not behave the way ordinary problems do. We must train our students as well as the researchers in doing this kind of new experimental mathematics, because that is what the reality of applied mathematics really is.

I want to emphasize when I say teaching that mathematicians spend only a very small proportion of their time teaching future mathematicians. The overwhelming majority of the time spent teaching is spent teaching in service courses—future physicists, chemists, and engineers.

Well, all of this brings us to what equipment is in fact necessary. You hear a lot about the high technology university, but, you know, it doesn't really exist, or at least it doesn't really exist in any substantial numbers. Of course, there is the Carnegie-Mellon, and Cornell that I am so glad to belong to, where we are reasonably well equipped. But there also is the SUNY-Binghamton, the University of Michigan, which are perfectly respectable institutions, but where faculty and students have only extremely poor access to computers.

For faculty, it is usually a matter of writing a research proposal to some committee within the university, having to fund it out of funds that they got from an NSF grant, and then having no access to computer equipment or having to spend extra money for that. It is a really complicated business in academia in general to gain access to a computer. As for the students, more often than not, the present state of students' access to computers is that they get to hand in a packet of punched cards at some window and hope to get results back the next day.

When mentioning equipment, there are three things that people in funding should keep clearly in mind. The first is that whatever equipment you buy today, 5 years from now it will be obsolete and will have to be replaced. There is no such thing as equipment that really is a long-term investment. The second is that one has to make allowance for maintenance and for staff. Maintenance typically costs 10 percent of the cost of the computer per year. Recently we were offered, at the mathematics department at Cornell, a mainframe IBM computer. The problem is that the maintenance alone is not far from the salary of 10 full professors. It was completely inconceivable that we would be able to afford the maintenance out of our own funds, even if the equipment were given.

Another very important point, especially from the point of view of the teaching computers, is space. You get 300 microcomputers so that there is at least one microcomputer for 10 students or 15 students, which is, roughly speaking, what is necessary, and you need to put them someplace. Well, mathematics departments were designed before computers, and there is no space available, in general. I think, in the final analysis, building the necessary space will be more expensive than all the other components of computerizing universities. Building a building is extraordinarily expensive.

Still, in conclusion, there is really much to be hoped. If we are able to use the fundamental algorithms of mathematics to model airplane wings, to chart the deep structure of the earth, to improve pistons within cars, or to model the population of fish on the grand banks, there is really much to be hoped from such things. Already we are seeing it to an enormous extent. The cars now get, roughly speaking, twice as many miles to the gallon as they got 10 years ago, and most of the credit for that should be given to the improved performance of the engines and the improved aerodynamic properties of the cars, which would have been impossible to design without supercomputers modeling the parts before they were ever built so that they could make thousands of modifications rather than the one or two if you had had to build an actual model and put it through a wind tunnel to find out what its aerodynamic properties were going to be.

I think that in every single area of manufacture and of exploitation of natural resources, applications of these fundamental and sophisticated algorithms, all of them essentially pure mathematics, are going to be central to the improvements that we can expect in all of these fields. Equally as important as improving the algorithms themselves—that is the job of mathematicians as researchers—is forming a whole generation of scientists and engineers who are able to use these techniques, and that is also our job as teachers.

Thank you very much.

[The prepared statement of Dr. Hubbard follows:]

Testimony regarding

THE IMPACT OF COMPUTERS ON MATHEMATICAL RESEARCH AND TEACHING.

To be given before the House Science and Technology committee,
September 11, 1985,
by John H. Hubbard.

Introduction.

As recently as twenty years ago, applied mathematics was restricted to very special, simple problems. The equations describing realistic problems were available, but they are untractable by analytical techniques, the classical techniques of paper and pencil.

The advent of the computer has changed all that. Nowadays, airplane wings are designed to minimize shocks using the equations of fluid dynamics, oil exploration uses the theory of inverse scattering, Josephson junctions (the fast switches of the next generation of computers) are analyzed using the equations of quantum mechanics. In all branches of applied science, the fundamental equations are being used to model realistic and interesting systems.

All the problems above require very elaborate mathematical techniques, of a sophistication that no engineer or chemist, and only very rare physicists, would have been exposed to just a few years ago; even today the engineer who can deal with such tools is exceptional. In fact, the algorithms were frequently known, usually as part of an abstract theory known only to a few mathematicians; the computer has given us the ability to implement them, and has brought them down to earth, or rather into the laboratory.

These techniques need much further study to achieve their full promise. Recent advances in computer technology – in computer speed and in computer graphics – make this study posssible. A host of previously inaccessible problems are now open to investigation, and the computer brings new dimensions to mathematical research.

Mathematicians can, for the first time, have a laboratory analoguous to that of the physicist or chemist. Experiments can be done to test hypotheses, and such experiments can lead to new conceptual frameworks on which fundamental theory can be built

In the twenty-first century, I imagine that mathematicians will use computers as an essential component of their mathematical activity. I also imagine that their interactions with physicists, chemists, geologists, engineers, etc will be far closer than at present. These interactions are already far closer than they were ten years ago, and I give computers much of the credit for this.

However, despite the publicity about high-tech universities, the proportion of mathematicians and students actually using these new possibilities is small. Some of this is surely due to inertia, but lack of equipment, facilities and staff are also important.

Why Differential equations?

In this testimony, I want to give from my own experience some examples of the sorts of things mathematicians do with computers, and what benefits might be expected.

Computers are used in many fields of mathematics: algebra, logic, probability among others. I will speak here only of the field I know personally: differential equations.

All the examples mentioned at the beginning pertain to differential equations. Differential equations are the main device used in making mathematical models of real systems. The real system in question might be as grandiose as a galaxy, as useful as an airplane wing or the piston in a car's engine, or as far removed from mathematics as the populations of fishes on the Grand Banks. What these systems all have in common is the simple but very important observation: the forces are simpler than the motions.

The most classical example of this is Newton's description of motions of bodies under gravity. The forces are extremely simple: bodies attract with a force proportional to the product of their masses and inversely proportional to the square of the distance separating them. Yet the motions caused by these forces are extremely complex, including for instance the braided rings of Saturn.

This philosophy -that the forces are simpler than the motions-leads to the following rule: when making a model of a system, you should not think of describing its motion; you should think: If the system is in a given state, how is it being pushed. Of course, an instant later, it has been pushed into a new state, so it is being now being pushed differently.

A differential equation is precisely this: a description of how a system is being pushed as a function of its state. Solving the differential equation means understanding the motions that the forces imply. This approach to modeling systems has been so successful that all the fundamental equations of science are differential equations.

So what's the problem.

Unfortunately, mathematicians have discovered that even after a scientist has reduced the description of a real system to solving a differential equation, he may not have gained very much. Even though the solution of the differential equation is a purely mathematical problem, in principle requiring only paper and pencil, it is often intractable. Even simple differential equations can have extraordinarily complex solutions.

The first clearly to understand the magnitude of this complexity was H. Poincare, a French mathematician (1954-1912). King Oscar II of Sweden offered a prize for the solution of the 3-body problem (the motions of three bodies under the influence of gravity). Poincare won the prize, not by solving the problem, but by showing that it was unsolvable in the way in which previous generations had attempted; at the same time he gave a glimpse of the extraordinary complexity inherent in the motions.

Largely due to the great difficulty of the field, the study of differential equations fell from favor. Although great progress in the field was accomplished between 1910 and 1970, largely the work of G. Birkhoff in the USA and A. N. Kolmogorov in the USSR, the field lost its position as the central topic in mathematics.

Over the last 15 years, the field has come back. There is no doubt that the availability of computers and of computer graphics has been of great importance to this rebirth. One consequence is that mathematics is also growing closer to its applications. Many people, both mathematicians and scientists from other fields, had regretted the way mathematics had drifted away from its sources in physics and other natural sciences, but this drift has now been largely reversed.

Experimentation.

What computers can do for mathematicians studying differential equations is to enable them to perform experiments. If you are unable to

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figure out how the solutions behave, go and ask the computer. There are algorithms, many of them, which approximate solutions. They require a great deal of computation and would be tedious in the extreme to carry out by hand, but this is just what computers do well. Typically, in this sort of computation, minutes of computer time are comparable to man-years.

Having computed an approximation to a solution, you face two immediate problems:

Displaying your result;
Evaluating how trustworthy it is.

Computer graphics is the answer to the first. If tabulated, the information in one of my pictures would fill a small book; getting a grasp of what was described would probably be impossible. In my experience, a computer is next to useless without a good graphics display, and I think that computers are contributing so much more to the field now than ten years ago largely because of the increased availability and quality of computer graphics.

The second -evaluating how trustworthy the result is- is more problematical, as it is usually impossible to evaluate the errors that creep in during a long computation. The best approach is simply to extract the salient features from the drawing, and to try to prove that they are real, and not artifacts of the computation. In the final analysis, the job of mathematicians has not changed; they still must make precise statements and prove them. The computer is just a (big) help in figuring out what the statements should be.

Actually, the statement above is not quite correct. Success breeds success. The field of differential equations has met with remarkable success recently, and has attracted a correspondingly large number of students. As such the the computer has changed the agenda of mathematics.

Newton's Method.

As an example of the procedure above, I will speak of Newton's method. This is not quite a differential equation, but an iterative algorithm for solving equations. In general, an iterative system consists of a transformation, where the main point is that you use the result of the previous computation as the input for the next, and repeat the process over and over again. In that sense they are similar to differential equations: they tell you where to go in terms of where you are. The theory of differential equations and of iterative systems are usually lumped together in dynamical systems.

Newton's method is an iterative system. If you wish to solve an equation, you start with a guess, as a seed for the computation. Then Newton's method gives you a transformation which if iterated will improve your guess, giving a sequence of values which in good cases converges to a solution of the original equation.

It is difficult to overstate the importance of Newton's method: solving equations is something mathematicians, not to mention physicists, engineers and more generally anyone involved with mathematics has to do constantly. Newton invented his method in order to solve an equation involving the eccentricity of elliptical orbits, but the method is generally applicable, and by far the algorithm most commonly used to solve equations. Newton's method is to applied mathematics what nuts and bolts are to engineering: unnoticed but essential to all applications.

In view of this it may come as a surprise that no one understands what Newton's method actually does. All that is actually known is that if the original guess is sufficiently good, the iteration will converge to the desired solution. If the original guess is not sufficiently good, Newton's method may converge to some other root, or not converge at all. Of course, you usually use Newton's method because you don't know the solution, so this is a very serious difficulty.

I write from experience. In 1976, I was teaching elementary calculus in Paris. Those were the days of programmable calculators, and Newton's method is one of the few programs sufficiently short to fit on those primitive machines. So I proposed to teach Newton's method, specifically to solve cubic equations, i.e. an equation like

$$x^3 + 3x^2 - x + 1 = 0 \ .$$

But the longer I thought about how to intelligently choose an initial guess, the more clearly I realized that I had no idea how to do it. I soon discovered that my colleagues had no idea either, so I went to a computer, and performed my first computer experiment. Start with an array of guesses, check to which root (there are three of them in this case)

Newton's method leads you, and color the original guess according to the root.

You can see for yourselves the picture that emerged. Although now we understand these pictures quite well, and their classification is in sight, at the time these pictures caused a revolution in the field. I dare say no one would ever have understood Newton's method for cubics without the help of computers and computer graphics, and it is not for want of trying. Exactly one hundred years ago, Cayley solved the corresponding problem for quadratic polynomials, which is misleadingly simple, and announced that in a forthcoming paper he would solve it for cubics. The paper appeared in the first volume of the American Journal of Mathematics, the first mathematical journal to appear in the USA. Needless to say, the announced article never did appear, but I hope (with my student Janet Head) to conplete his work.

In any case, I have never looked back. Ever since, I have viewed computers and graphics as essential tools to my research. Many others had the same experience.

Research and Teaching are linked.

Almost all mathematicians are also teachers. Not just teachers of future mathematicians; by far most of the time spent teaching is devoted to service courses, taken by future engineers, chemists, etc. Some view their teaching duties as a chore, but I do not. One reason is that I do not find even elementary calculus a closed subject. Innumerable avenues lead off from the usual curriculum, the exploration of which would be of great interest. Newton's method as described above is just one example. Clearly the creators of the field knew this, simply they were unable to penetrate them. In many cases the computer can be used to clear a path. I find these problems, often down to earth and easy to understand, more interesting than the problems which occur in more advanced fields. Also, I can take even beginning students along for the trip, which they often enjoy.

This investigation of subjects outside of the main curriculum is far from the only, or even the main use of computers in teaching mathematics. All teachers in the field know all too well the great demands that abstraction makes upon the students, and the corresponding appalling rate at which students leave mathematics, to the great loss of all sciences. The ability to experiment with the objects of even the most classical parts of the curriculum can work wonders in bringing these abstract flights of fancy down to earth and within the student's grasp.

I have for the past four years taught a course in applicable mathematics at Cornell University, taken primarily by juniors in physics and engineering. The curriculum has been extensively modified, so as to include the use of computers throughout. The changes are a success. this course was traditionally the opposite of popular, but now the enrollment has more than doubled, and the complaints are considerably fewer.

The introduction of computers in the mathematical curriculum is critically important. At the same time that it made advanced and abstract topics more concrete for students, it also made them central to applications. Whereas previously engineers might have survived using the tables and rules of thumb of the standard handbooks, nowadays they will be expected to design parts of a car body or buildings in such a way as to optimize the appropriate characteristics. If they are unable to master the necessary mathematics, their work will be obsolete before they start. A university that fails to train its students in these topics is giving them an obsolete education.

Already all the major automobile and airplane manufacturers own supercomputers for this purpose. These computers are running software which includes very sophisticated algorithms, far more complex than anything used 30 or even 10 years ago. The algorithms involved in oil exploration are even fancier. These are techniques which students must learn.

What equipment is necessary?

Every mathematics department should have a substantial computer: a Vax, an IBM 4341, or some equivalent super-mini. This should be accompanied by appropriate terminals (particularly graphic terminals) and hard-copy devices. Each faculty member should have a work-station in his or her office, linked to the central computer.

One problem with the present funding system is that individuals, not departments, are funded. Only occasionally will one individual be able to justify the expense of such a system; typically an individual is allotted $5000 with which to purchase computer time. Shopping around for an appropriate computer is then a time-consuming process, and lack of ready access makes using the computer a chore.

At Cornell, I have witnessed the extent to which easy access to equipment has changed the outlook of the staff toward computers. Many professors, even among the older ones, have become comfortable with computers and use them in their research and teaching, to the great benefit of themselves and their students.

The problem of giving students access to computers is more complicated. I think that every student should have ready access to a micro-computer, perhaps a Macintosh or an IBM PC with adequate graphics. This requires about one computer for 10-15 students.

We hear in the press about the computerization of the universities, but it is still far from common. I have recently written a textbook on differential equations. Editors are quite prepared to publish it, but they want no direct reference to computers in the text: too few universitites have the equipment to use a text which really incorporates computers. And when the book was sent out to referees, only one of the four, all professors at respectable institutions, was able to locate the right kind of computer on campus.

In discussing equipment, four points should be kept in mind:

- The equipment will be obsolete in 3 to 5 years, and will need to be replaced.
- Adequate provision for maintenance should be part of the funding. Maintenance typically costs 10% of the acquisition cost per year.
- Adequate funding for staff and software should be part of the funding. Buying programs is expensive, and writing them is more so. Few professors can spare the time required for good programming. I am myself quite a fair programmer, but without the help of students working with me I would never have done a fraction of what I have done. These students need to be paid.
- Finally, there is the question of space. At Cornell, it has been quite hard to find space for 300 micro-computers; mathematics departments in particular were designed long before this invasion. Somehow new buildings will have to be built; this may end up being the most expensive part of the program.

What benefits can we expect?

All sorts of problems, in the design of engines and other mechanical devices, in the management of ecological systems, in exploration and exploitation of natural resources, or in tailoring a molecule to some particular purpose, are amenable to the sort of mathematical modeling described above. In all these fields we can expect great improvement from a successful mathematical exploration of the corresponding model. We are already seeing part of this in the improved gas usage of cars and of airplanes; the present generation was designed and tested on a computer before any physical models were built.

This also saves a lot of time and money, as computer testing is a great deal quicker and cheaper than wind-tunnel testing, for instance. Before long, we can expect all products to be modeled and tested on computers before they are built.

In all the examples above, the key mathematical tool is differential equations. Further study of the general properties of such equations is one essential ingredient to successful applications. Another is training a generation of scientists in their use.

DISCUSSION

Mr. **Brown**. Thank you very much, Dr. Hubbard.

If I may begin with one or two questions, first let me say, as I did yesterday, that you gentlemen, while much of your testimony has been over our heads, I think have clearly conveyed the significance of the changes that are taking place as a result of the major revolution in information technologies, which include both computers and communication that is affecting science today, and we are very grateful to you for helping us to understand that more clearly.

Dr. Hubbard, I have seen some reference in testimony and periodical literature that in the field of mathematics, there has been an inadequate amount of funding for research in pure mathematics as a result of perhaps overemphasis upon funding for computers. I don't get that message from your testimony. You seem to be saying that a lot of the progress in mathematical research has been due to computers and that we need more computers, if anything, instead of a change in the proportion of the funding. Can you straighten this problem out for me a little bit?

Dr. **Hubbard**. As you are surely aware, NSF funds essentially all mathematical research. The mathematical budget of NSF has decreased by a factor of approximately two over the last 12 years. I am not really an expert on this kind of thing; I mean that is not things that I really know about. This has had, of course, an effect on the incomes of mathematicians and on the way the profession of mathematician is viewed. Also, I am perhaps in a minority—I think a strongly growing minority—of mathematicians who use computers, and I support my view that computers are indeed important. But, of course, they don't really replace income, summer salaries, and so forth.

If you decrease the proportion of funding for mathematicians in the sense of decreasing support for graduate students and decreasing summer salaries for researchers in favor of computers, well, of course, one consequence is that you decrease their income. One should expect that to lead to complaints. I do think that computers are tremendously important, but the desirability of the profession itself is also important. If you cut funds—what can I say? Inevitably, people will be unhappy.

Mr. **Brown**. That is true.

One of the things that I don't understand fully, amongst many others, of course, is the reference that I think all of you make to the term "algorithms" and their use in, I guess, programming computers, utilizing computers.

You, Dr. Hubbard, draw some parallels or analogies between algorithms and differential equations. I would appreciate it if any of you could clarify just what it is that we mean when we refer to algorithms in connection with computers.

Dr. **Pensak**. Well, to us an algorithm just means a computational procedure, a recipe, if you will.

Mr. **Brown**. It is something that you can program into the computer?

Dr. **Pensak**. Yes.

Mr. **Brown**. Is it invariably a mathematical formulation, or is it in the form of an equation?

Dr. **Pensak**. In most cases in the form of an equation or a way of solving equations or of combining equations.

Mr. **Brown**. In your field, though, of chemistry, I have difficulty in visualizing how you can formulate a complex molecule, for example, using an equation. Do you have equations that describe complex organic molecules?

Dr. **Pensak**. No; as Dr. Hubbard said, mathematics does not at the present time precisely describe anything bigger than a hydrogen atom. So what we have to do is make a series of approximations to what the behavior of the molecule should be in little pieces and then try to combine those and hope that the approximations are adequate.

That is why there are many different techniques for calculating molecular properties, some of which are very simple, because they don't make many assumptions; they assume that each atom is round. You can get more and more sophisticated in your computation and recognize that the electrons don't go around a nucleus like planets go around the sun. The more complicated the approximations that you make, the more computer time that is required, and then the more effort you have to go into to make sure that your mathematics of combining these approximations is efficient.

Mr. **Brown**. Well, that helps a little bit. [Laughter.]

Are you sure it was Newton that discovered the calculus, Dr. Hubbard?

Dr. **Hubbard**. As you are surely aware, there is a debate among the historians. To my mind, in any case, the discovery that the right way to describe a system is through a differential equation is Newton's, really, greatest discovery, and he set the agenda for how to describe nature. It is still an agenda that is followed to the letter. Every fundamental equation of nature is a differential equation, and both of the two gentlemen, even in the most applied subjects, are actually solving differential equations in their work. He discovered the notion of a differential equation. He perceived that saying how bodies were going to attract would in fact imply specific motions. This was a really new insight which I think has been perhaps the most important insight in the history of humanity. It started the scientific age.

Mr. **Brown**. Dr. Gilbert, your testimony with regard to applications in seismology and geosciences, of course, is particularly interesting to those of us in California who have been concerned about earthquakes for some time. Your description of the formation of tsunamis leads me to wonder if we could make an argument here that would be attractive in Congress for support of this particular view of the science on the grounds that it might give us a predictive capability that would save us a considerable amount of money, which always appeals to Congressmen, of course.

Do you happen to know offhand what kind of damage, historically, we have had from tsunamis? And give us an idea how we could compare that with the cost of an adequate monitoring system which would allow us to give warnings of tsunamis. I won't go into the more complicated problem of earthquake prediction on land right at this point.

Dr. **Gilbert**. With regard to tsunamis, I think it is the Pacific coast that is most vulnerable. I don't know of any historical records of tsunamis along the Atlantic coast or the gulf coast.

In the case of the Pacific coast, earthquakes in South America, earthquakes in the Aleutians, earthquakes in the Kamchatka Peninsula of the Soviet Union and in the Japanese Archipelago are the primary locations of earthquakes that cause tsunamis.

Again, the historical record is very short. We know that the 1964 Alaskan earthquake caused a mild tsunami that was severe in a few places along the coast of Washington, Oregon, and northern California, caused some loss of life and considerable property damage. We know that the 1960 Chilean earthquake caused a relatively large tsunami about 1 meter, a little more than 3 feet in amplitude, in southern California. Fortunately, it occurred at low tide, so there wasn't very much damage.

I believe that the danger around the Pacific basin from tsunamis is greater in South America and perhaps in the Hawaiian Islands, and along the coast of Japan and Eastern Asia, than it is along the coast of California. And, of course, it is very important in the case of the coast of Alaska, especially the Port of Valdez, which is the southern terminus of the trans-Alaska pipeline.

One of the problems that you have in tsunami warning is simply the problem of time. If there were an earthquake in Japan or Kamchatka or South America that was predicted to cause a severe tsunami in Alaska, and if this scheme that I mentioned in my written testimony were implemented, then you could probably protect the coastline of Alaska. You could evacuate people, beach boats, shut down pipelines, that sort of thing. But if the earthquake itself is in Alaska, as the 1964 earthquake was, then it is over before you know it, and you don't have a chance, using seismological methods, to make an early warning. Still, I believe that there is a reason to think that this is something that is worthwhile doing in the long run, even if the frequency of tsunamis is quite low, even if they only happen every, say, four of five times a century.

The fact that you can save—as populations along the coast grow—that you can save—I don't know what it would be, 10,000 lives, 100,000 lives? I think it would be worth the effort. I don't want to give the impression of putting a dollar value on human life, but I think it is something that would preserve life and preserve the works of man.

You have to realize that there are many places in the world where there have been tsunamis, historically, where the time between earthquakes, if they do have a cycle at all, is very great. There was, in the middle of the 18th century, a big tsunami in Lisbon, after the great Lisbon earthquake, which, of course, wasn't in Lisbon at all; it was offshore Gibraltar. That caused tremendous damage, the earthquake itself and the tsunami that followed.

I think that the fact you cannot predict earthquakes at the present time—when and where and how big they are going to be—is a reason to mount a tsunami warning effort if it represents technology that is easy to implement. I believe that, in the next 5 to 10 years, it will be, with satellite transmission and higher speed computers, quite feasible, at a reasonable cost, to integrate that into the seismological data processing effort on a day-to-day basis.

So I believe that there is the argument, even though only a small fraction of the population of the United States would be primary and direct beneficiaries. I think the same thing is true for things like hurricane warnings along the Atlantic coast and the gulf coast. Every now and then, there is a hurricane along the Pacific coast, but not very often. The same thing is true of tornado warnings, hail warnings, snow warnings. A fraction of the population benefits in any one case, but it is all to the public good, and I think it should be supported.

Mr. **Brown**. Well, this committee has been interested for some time in the enhancement of our capabilities in many of the areas that you have mentioned—a better understanding of climate and weather and a better understanding of earthquakes. And, of course, now we are being called upon to fund increasingly expensive and complex monitoring and analytical systems based upon these new computer capabilities and so on.

Before long, I think the committee will be considering proposals from the scientific community for a global scientific system under this general rubric of international geophysical/biophysical program, which would, I think, incorporate many of these kinds of sensors and analysis of Earth phenomena on a truly global basis. That will be expensive, and it will be something that will require many years to accomplish, involving computers, satellite communication links, and many other things.

Now, Congress is enthusiastic about doing things of this sort when the money is available. They are more enthusiastic when they can see the financial benefits that perhaps might be considered as side effects of this, which is why we pursue this line of questioning sometimes. Some of us might feel that it is valuable just from a pure science standpoint, but we are spending scarce public dollars, and the public likes to see some additional justification for this when they can.

Are you, incidentally, familiar with the plans developing in the scientific community for this international geosphere/biosphere program?

Dr. **Gilbert**. I am, yes.

Mr. **Brown**. In your opinion, is the work that we are doing in Parkfield with regard to the development of sensors and predictive capabilities in advance of what the Japanese are doing, or is it comparable to what they are doing?

Dr. **Gilbert**. Well, there is a tremendous amount of cooperation between the Japanese Earth scientists and American Earth scientists, and I would say that the efforts are complementary and very similar in terms of technical capability and scope. The problem, of course, is more severe in Japan in terms of the frequency with which earthquakes occur and in terms of the fraction or percentage of the land area and population that is affected. But, even so, I believe that the efforts are comparable in size and in technical quality.

Mr. **Brown**. Mr. Walgren, do you have any questions?

Mr. **Walgren**. Well, I just wonder about a couple of things. I have always been concerned at how we have trouble developing the political support to commit the resources to this area, and inadvertently, we do everything, or do much, through the defense rationale.

As I understand it, by committing the size of resources we have through the defense community, we have pushed the computer capability tremendously. But I couldn't help but note in your testimony, Dr. Pensak, your statement that we are arraying 65,000 processors through DARPA for an autonomous land vehicle project. I guess I understand that we can gain as much from that as arraying them for perhaps any other purpose, and that the intellectual foundation for that is probably very broadly applicable. And yet it seems wrong that whenever we are doing this, we find DARPA or some other defense base for it. Can I ask for just very quick reactions as to whether or not we are substantially hindered by our need to do this through the defense community?

Dr. **Pensak**. I don't think we are hindered by it, but I think the rest of the scientific community is somewhat hindered because the defense agencies tend to be less than forthright with rapid dissemination of nonsecurity-related information, so we tend to have to wait sometimes several years after developments like this are funded by the Government before we can begin to learn enough about the technology to begin to apply it in our areas.

Mr. **Walgren**. Would any of the other gentlemen like to quickly respond to that thought?

Dr. **Hubbard**. Oh, yes; I would.

In 1972, I believe it was, the Department of Defense decided that they would fund no further research which did not have a direct application to defense purposes. This eliminated the Air Force contracts and Army contracts that many mathematicians held at that time. Indeed, very little of mathematics is directly applicable in this sense. There is a lead time. Mathematics develops algorithms. No doubt they are useful in defense; they are useful in many other things, also. But it is hard to make a case that they are directly related to defense.

The fact that the defense budget is the large research budget of the U.S. Government has had a drastic effect on the funding of mathematics. Mathematics is funded almost exclusively through NSF, and NSF is tiny as compared to the Department of Defense. Yes, there is no doubt that channeling research money to other fields through the Department of Defense has had a drastically unfavorable effect on mathematical research.

Dr. **Pensak**. I have to concede I am coming at it from a very different point of view because I don't depend on any Federal funding for my work at all.

Mr. **Walgren**. Well, I suppose this is fundamentally a question of appreciation and how we can develop in our society the ability to get in place resources that come from a relatively spoken-for pot in the way that would have the best effect in your areas of interest.

It is striking how we have instinctively, like everything, done it through the defense rubric. The Synthetic Fuels Corporation was known as the national—I don't know what it was. It was something that was very military in the title under which it moved through the House of Representatives. I guess it is a political problem, really, that we clearly have not solved.

I gather—and it is obvious that these kinds of changes do change the things that scientists want to do and their behavior, if that is a general word for what scientists do. Would anyone like to make quick comments, more than you have in your testimony, or in addition to what you have in your testimony, about how the information technology has changed the behavior of science and the management of science in research laboratories?

I gather there are two elements of this, one simply descriptive of how do scientists behave now that they didn't behave then, but implicitly, there is probably a plus and minus to those changes in behavior, and the question is, are there down sides to the changes in behavior and attitude and approach that scientists are using that we should be trying to minimize?

When we set up a big bureaucracy in the Federal Government, we walked right into a lack of decisionmaking capability and a mind-set that is not the best under some circumstances, and we have sort of learned not to expect things from a large bureaucracy that we would have expected from individuals who came in accepting direct responsibility. Are there similar kinds of detriments or approaches that we should be warned against as you see these sorts of changes in information technology changing the behavior of scientists and the training of scientists that you would like to flag for this study that we are involved in?

Dr. PENSAK. Sure; I have got one that I think even applies in the university environment. Computing in our company is going up—this is scientific and engineering computing—by something like 150 percent per year, compounded annually, and the mania to buy personal computers as a way of getting around funding restrictions—and we do have our own sets of funding restrictions as well—has forced people to put personal computers in their laboratories.

We have one case fairly recently where an individual had a program that was running on the central facility, and he was able to run it about 50 times a day in conjunction with experimental work, and it was costing $5 a run or some arbitrary value. Well, he had the perception that his funds were running out, so he bought a personal computer, spent 5 weeks converting this program from Fortran to BASIC, because that is all his personal computer could use, and another 5 weeks learning the operating system. This is so much slower than the mainframe, he is now able to run the thing only 10 times a day. So his net productivity has gone down. He in fact wasted, we figure, well over $100,000 in effective value of his time by doing this move.

I think what you have to be afraid of is that personal computers are becoming an addiction right now, and there is so much incompatibility between them. We have people who will spend literally days trying to figure out how to get a data file from their HP personal computer over to the IBM personal computer.

Mr. WALGREN. But it is interesting why they would be becoming an addiction, because in a sense the personal computer—does it represent an assertion of individual control or individual, I guess, control over his environment or time or product?

Dr. PENSAK. Very definitely; you remember the old line, "War is too important to be left to the generals"? Well, we have an analogy: "Computing is too important to be left to the computer centers." In our organization, for example, no one who is in any position of responsibility in the computer center has done actual chemical research themselves. They are highly talented and trained people. They know their business very well. They don't understand our business to be able to develop a facility which is as supportive of research as the bench scientist would like to see, and as a result, he tries to run away from that, gets his personal computer, and then everybody winds up wasting money.

What I would like to see is if we could find a way to make computer centers funded by the Government or anybody else more responsive to the needs of the researcher. In our organization's perception, production computing is totally different than research computing, and they cannot be allowed to mix, and as such there are different standards, different levels of support. That is something I think you could——

Mr. WALGREN. But how could a central facility, particularly a Government facility, effectively take your work from your researchers and run it if even the computer center operators which you now have are so disjunctive with the researchers that you don't trust them?

Dr. PENSAK. It is not so much a question of distrust. It is more one of just organizational sanctioning. By and large, the large facilities that we have seen both inside and outside the company see as their mission just providing CPU cycles, becoming a computer utility. If the Government could, in the facilities that you run, sanction more research per se and integrate the computer science research and the mathematics research with the people who run the data centers so they could be more responsive, I think that would help an awful lot. Am I making any sense?

Mr. WALGREN. Well, it takes me a long time to understand things, and I am sure you are making more sense than my immediate comeback might indicate.

Dr. PENSAK. The people in our shop who buy personal computers usually do it for the reason, "I can't get the data center to give me what I need to do my job. Nobody cares." And I think we see a lot of that in universities as well.

Dr. HUBBARD. Yes, there is no doubt. I think that the computer centers have an overemphasis on equipment as compared to their emphasis on staff.

Mr. WALGREN. All right. So what is going on here is, if they are driven to the personal computer because they are feeling an insufficiency from the computing center as opposed to philosophically wanting to have the power of individual existence and individual control, then it is simply this lack of sensitive service by the computer center that is the problem here.

Dr. PENSAK. I think too many really sincere scientists do not want to waste the time learning how to run MS/DOS on the PC. They would like to get down to their science.

Mr. WALGREN. So our computer services are not serving the scientists well, and what you are saying is there is an emphasis on equipment as opposed to staff at that point.

Dr. HUBBARD. I would like to comment that there is also the aspect that trying to learn CMS on a mainframe is——

Dr. PENSAK. Ghastly. [Laughter.]

Dr. HUBBARD. I mean, trying to operate these computers yourself rather than having somebody who is conversant with the science you are trying to do and can write the programs—I mean, there is a terrible lack of productivity in trying to learn how to operate these big machines, and the small computers.

It took me probably 5 years to get the first pictures of this sort, largely because you have to be able to define a big file, you have to be able to get it from one tape deck to a graphics terminal. Nobody knows how to run the graphics terminal. Nobody who knows one thing knows anything else. I mean, it is a huge effort and waste of time which could easily be compensated by having staff members who are specialists in scientific computing assigned to the center.

Dr. PENSAK. To add to that, if I might, in the past, the Government has funded some very worthwhile experiments like the National Resource for Computation in Chemistry, which, for procedural reasons and the like, did not continue to exist. But if you could create centers of excellence where, if you can't get the help locally, at least you can call an 800 number and somebody there will understand you and want to listen to you and maybe have some advice on how to solve the problem, that might be a first step.

Mr. WALGREN. Then the question is what would the appropriate role of the Government be in meeting this kind of need and developing data bases and related services for scientific research. Do you think the Government can be sensitive enough to provide those services well, or—I guess I have an initial reaction that I don't know whether the Government has the will to get into providing this kind of service, almost because our concept of information is more related to libraries, and libraries have always been a function of local government or Andrew Carnegie, one or the other, but not really the Federal Government.

I have seen lots of Congressmen's eyes sort of glaze over when we start to talk about information, because it is just too abstract, and it doesn't have the flesh and blood of problems that can be used to generate public support and public interest. So I guess the first question is, should we be getting the Government—feeling the responsibility for the Ggovernment in these kinds of computing center areas, and do we have the ability to get the funds there, politically? Would either of you gentleman like to comment on those areas?

Dr. GILBERT. I would like to address a part of the question. I think one of the needs, so that you don't have isolated centers and isolated personal computers, is the need for a communications network that would enable a person with a personal computer to interact with any one of a number of centers where hardware is concentrated, of necessity, so that the program that runs in personal computers and another program that runs in the center's, let say, supercomputer are actually two parts of the same program operating over a large communications network, so that the person with the personal computer can interact with the entire center's system in an interactive way and thereby not have to deal with personalities unless it becomes absolutely necessary to learn something of a very specific nature about, for example, a graphics work station or an output device of some other kind. By having such interactivity and such a good broad-band and, shall we say, expensive communications network, you increase the productivity of the individual person, whether that person is a scientist or a lawyer or an engineer or a school teacher, in using the large-scale computers, using the personal computers, using the special devices, in a very effective, productive way.

Now, whether there should be a U.S. Government national network is another question that I don't feel qualified to address, but I believe that encouragement of various kinds—usually financial encouragement is what is meant there—to develop broad-band national regional communications networks to make this possible is, I think, a very desirable activity.

One example that is not my own but that I believe I heard at a meeting of the House Committee on Science and Technology of Florida State is the analogy with the interstate highway system. You want to be able to make it possible for people to have a tremendous amount of traffic going back and forth in a meaningful way relatively easily so that if there is a computer center in, say, Boulder, Colorado, and a scientist at Cornell or DuPont wants to use the special facilities there—make color movies of the way molecules vibrate or make color movies of the way solutions of cubic equations converge—that person can look at help documents online through the communications network on his personal computer in a remote place and get to the point that programs run, even if they don't run correctly. Then you would have something to talk about. Then you could call up a consultant and say, "I followed pages so-and-so in the help document, I did this and that, and it didn't work; please help me." Then you are getting a quantitative dialog started and people can make progress.

And so I believe that the communications network is almost just as important as, if not in some cases more important than, the machinery and the operating systems for the computers themselves.

Dr. **Pensak**. One aspect of this, I would like to add, in Toefler's book, The Third Wave, he points out very eloquently that the technological revolution is taking place at a much more rapid pace than either the industrial or agricultural revolutions, and that mankind is just not adept at that rapid a degree of change. I think we are all chafing at trying to work with and manage a technology that is moving far faster than we ever thought it could. So you are always going to hear some bitching and crabbing no matter what happens. So take it seriously, but not too seriously.

Mr. **Walgren**. Thank you.

Mr. **Brown**. Any questions, Mr. Slaughter?

Mr. **Slaughter**. No.

Mr. **Brown**. Dr. Gilbert, one of the supercomputing centers being funded by NSF is going to be at your institution, isn't it?

Dr. **Gilbert**. Yes.

Mr. **Brown**. Is that sufficiently far along that you have any opinions as to whether that is going to contribute to the productivity of your operations and other scientific operations in the region?

Dr. **Gilbert**. Let me summarize very briefly the status of what we call the San Diego Supercomputer Center.

First of all, it represents a consortium of 19 research institutions. For example, the University of Maryland will be connected by a broad-band communication link to that computer center.

Mr. **Brown**. Is that a satellite link?

Dr. **Gilbert**. I believe that will be a satellite link. I don't believe the actual bids have been chosen yet, but in a matter of days, or before the end of the month, that decision will be made. The Universities of Michigan and Wisconsin will be connected to that center, and the University of Utah, the University of Washington, the University of Hawaii, and the Kit Peak National Observatory in Tucson, Arizona, all outside of California and quite distant from that center, will be connected, so it will look to them like the computer is right there. We will be using an interactive time-sharing system.

Inside California, several campuses of the University of California—Berkeley, Los Angeles, San Francisco, and San Diego—Stanford University, Cal Tech, San Diego State University, some research groups like the Salk Institute and the Scripps Clinic in San Diego all will be connected so that there will be a wide variety of research all the way from plasma physics to membrane dynamics to molecular modeling; in the case of San Francisco, pharmaceutical design; a tremendous variety of activity.

The system is going to be up and running, we think, in January, and by having the interactive system and the fairly broad-band communications network, we think that all of these institutions, which represent hundreds of thousands of students and thousands of faculty members, and maybe a third of the NSF research budget, will have very good access to the supercomputer facilities.

One of the things that we will have is the capability that anyone with a not-too-unusual personal computer can have the illusion of actually doing screen editing and time-sharing computing on the San Diego Supercomputer, regardless of that person's geographical position.

So I believe that it will make a very positive contribution in the way that you are suggesting.

Mr. BROWN. These supercomputing centers then become sort of models of the kind of networks that we were talking about.

Dr. GILBERT. They are prototypical. I hope they are prototypical. That is the intent.

Mr. BROWN. Can you interact with Cal Tech on their seismological research with this computer?

Dr. GILBERT. Yes, indeed. We will be able, when the system is up and running early next year, to exchange data, programs, electronic mail, of course, manuscripts, reports, all through the network from the San Diego Supercomputer Center.

Mr. BROWN. We want this to succeed, and maybe Congress can have something like that sooner or later so that we can interact a little bit better.

Dr. GILBERT. Well, if you would like to have a link with San Diego, I will see what I can do for you. [Laughter.]

Mr. BROWN. Well, gentlemen, your presentation has been excellent and exciting in many ways. We are very grateful to you for being here this morning to help give us a little better picture of what is happening in this field, and we look forward to pursuing it more extensively.

Thank you very much, and the meeting will be adjourned.

[Whereupon, at 11:58 a.m., the task force recessed, to reconvene on Thursday, September 12, 1985.]

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THE IMPACT OF THE INFORMATION AGE ON SCIENCE

THURSDAY, SEPTEMBER 12, 1985

House of Representatives,
Committee on Science and Technology,
Task Force on Science Policy,
Washington, DC.

The task force met, pursuant to call, at 10 a.m., in room 2318, Rayburn House Office Building, Hon. Doug Walgren (acting chairman of the task force) presiding.

Mr. **Walgren**. Well, let us start and let me welcome all of you to this third session of the Science Policy Task Force on the Impact of the Information Age on Science.

In the first two days, we explored the ways in which information technologies have moved science forward and tried to explore how they have changed the conduct of science and what might be anticipated in that area. Today we will consider how the new technologies have increased scientific communication in reporting resources by permitting users in remote locations to access a distant facility to share programs, and data, and collaborate with each other.

We will be interested to hear from the witnesses that we have assembled today about the impact of information on the way science is communicated and disseminated and their projections on the way in which science communication will change in the future as a result of developments in technology.

We are very pleased to have each of you join us and want to express our real appreciation for your contributing to the discussion and the record that we make in the process of this exploration.

We have three witnesses, which will assemble in a panel and hear essentially from; Patricia Battin, vice president, University Librarian of Columbia University; Dr. Allen Newell, who is professor of Computer Science at Carnegie-Mellon, in my home area, and I certainly extend a special welcome to a friend from Pittsburgh; and Dr. John Brown, the principal scientist and director of Intelligent Systems Laboratories in Xerox Palo Alto Research. Welcome to the committee.

Statements are made part of the record without being totally read into it, and so know that if there is some way that you would like to diverge from what you might have prepared for the committee on paper, it will get incorporated in the record that we produce, and you should feel free to emphasize and underscore those points that you feel really should be focused on and elaborate on them in whatever informal way you would like.

With that, let me—we'll go in the order that we called the panel. Let me introduce then Dr. Battin.

STATEMENT OF DR. PATRICIA BATTIN, VICE PRESIDENT AND UNIVERSITY LIBRARIAN, COLUMBIA UNIVERSITY, NEW YORK, NY

Dr. **Battin**. Thank you.

I am honored to have the opportunity to discuss with you the concerns of research universities about our ability to provide the necessary quality of information services in the electronic age, and more specifically, access to machine-readable data bases and networks for scientists.

The capabilities of the new information technologies have had and will continue to have a fundamental and revolutionary impact on the manner in which academic research scientists acquire, use and disseminate information. The capacity to organize and manipulate information in machine-readable format by sophisticated retrieval systems and the use of Boolean logic has stimulated different ways of thinking about and conceptualizing scientific inquiries. The graphics capability of computers makes possible the creation of three-dimensional models in machine-readable form, which then become important tools for related and continuing research efforts in other laboratories and universities. Communications technologies, coupled with the widespread use of microcomputers, now support rapid global transmission of research findings, numeric and quantitative data, and informal collegial communications among individual scientists. As one scientist has observed, "Digitized information has become a way of life."

However, this new way of life has outpaced our efforts to conceptualize, develop, and finance the new infrastructure necessary for the full and productive use of the new technologies, which require compatibilities of hardware, software and network gateways on an international scale to meet the needs of the scientific research community. In addition to these organizational and policy barriers, the characteristics of information technology, which on the one hand permit an extraordinary expansion of the ability to create, store and disseminate information, also encourage the chaotic proliferation of information resources and permit unprecedented control of acccess to that information. The ability to control access to information by charging a fee per use has serious implications for the individual researcher as well as the university's capacity to provide the necessary information services to support scientific research.

Since unfettered access to information sources and open communication of research results have been the hallmarks of American scientific inquiry and research productivity, I would like to focus my remarks on the new barriers to this traditional access accompanying the powerful potential of information technology. In addition, the emergency of an information industry which views information as a commodity rather than a public good is causing an alarming shift in the perception of value from the intellectual quality of information to a value based on short-term market demand.

So we talk a lot about dissemination of information which the new technology makes possible in ways that we never imagined before. What we are failing to think about is an access structure, the creation of a substitute or new access structure so that you can also retrieve information as well as disseminate it.

Historically, the university has defined the responsibility for providing sources of information to faculty and students as a central function, mainly in the form of libraries. In our societies, we have had Federal, State, and local support of a library information infrastructure across the Nation which has provided what we call subsidized information open to all citizens.

The rapid increase of powerful microcomputers has expanded the dependency of scientists on new ways of manipulating, generating, recording, and disseminating information through the use of data bases and networks. But the use of microcomputers has mushroomed far beyond the development of an affordable infrastructure to support the convenient and coordinated processing or research data and scientific knowledge. Our bibliographic and computer networks were designed to be mediated through centrally managed service organizations—libraries and computer centers—and their protocols reflect that design.

Despite the sophisticated power of computers and telecommunications networks, the frustrations of incompatible hardware, software, and networks plus the lack of standardized protocols for organizing and retrieving information in machine-readable data bases lead most scientists to pick up the phone and call a colleague in their search for information. As one frustrated scientist reported: "Research today is 90-percent search and 10-percent research."

The following example illustrates the present chaos: A graduate student in a Columbia biology laboratory asked a reference librarian if she could find a table giving the complete protein sequence for *E. coli* RNA polymerase. She knew that the sequence had been completed in the last year and said that the work had been done by many different researchers who published their results in many different journals. She had also heard that the National Library of Medicine had a data base which might contain the answer.

Various books in the biology library supplied parts of the sequence, but not the whole sequence. Chemical Abstracts had many citations but not the actual data. Eventually, via the New York Academy of Medicine, the librarian made contact with a lab at the National Biomedical Research Foundation at Georgetown University. They had the sequence in a set of seven tables which they would run off and send to Columbia. They also told her that the National Institutes of Health had just acquired the data bases, and they would become public in several months. Then we found out, after about 4 or 5 months of this, that one researcher at the Cancer Research Center College of Physicians and Surgeons, Columbia University, had access to this data base and no one else knew it. That is a typical example of what we have now with no access structure in place.

The current array of networks—BITNET, ARPANET, CSNET, NSFNET, OCLC, and RLIN, plus the commercial facilities—were designed to connect centrally managed computer hosts which had the capacity to direct traffic. The widespread use of microcomputers has placed the technology in the user's hands and created the need for a global telecommunications network accessible to all scholars with standardized gateways, file transfer capabilities, and comprehensive user directions. There is also a conflict between funding sources based on political and organizational jursidictions and the scholarly need for access to the universe of knowledge regardless of location, format, or ownership. In addition, the magnitude of costs for capital investment in hardware, software, and networking equipment has added enormously to university budgets. The effectiveness of electronic dissemination is serious eroded unless everyone has convenient access. The proposed rise of AT&T costs has created further barriers to access by encouraging the spread of locally owned and incompatible networks in universities and corporations.

The very valuable data bases constructed in numerous laboratories around the world are not readily available. Their existence is communicated generally through the invisible network because of the lack of compatible electronic networks and retrieval capacities. As a consequence, much development work is proceeding in parallel with a high cost of redundant effort and expenditure of resources. There is no publicly subsidized international network coordination for the scientific community.

It is unfortunately true that the information needs of the scientific research community run counter to the imperatives of the for-profit sector, which views information as a commodity to be bought and sold. That philosophy is in direct conflict with the belief that information is a public good and not amendable to the traditional value structure of the economic system.

The imperatives of the for-profit section—maximized profits, short-term market demand, opposition to standards and compatibilities, and barriers to access imposed by competitive pressures—present enormous obstacles to the continuation of our national tradition of private and public subsidization of an information infrastructure available to all citizens. The Nation's research universities—both public and private—through their reserach libraries have combined with the federally supported Library of Congress, National Library of Medicine, and National Agriculture Library, and State, and local libraries across the Nation to acquire, record, preserve, and make available this country's intellectual heritage, regardless of its immediate economic value. There is no indication that the various commercial organizations marketing data bases and other information sources share these objectives, which are critical to our scientific community.

The traditional systems of peer review and quality control have not been adopted by most data base publishers. For example, there is serious and demonstratable concern about the quality of the numerical data bases. Many are very dirty, give no sources of their information, and access is very expensive.

A major concern for scientists is the continuation of the subsidized browsing capacity in the electronic environment. The control of data bases and networks by the for-profit sector has created a set of costs imposed directly on the information seeker. There is already evidence that this constraint influences the path of intellectual inquiry, the choice of research topics for the graduate student, and alarming variations in the level of potential productivity among the information haves and have-nots. Information costs have now become a visible influence in determining the thoroughness of a literature search by graduate students, a factor which erodes the overall quality of the research effort.

The recent OMB circular, "Management of Federal Information Resources," represents a significant change of Government policy toward the provision of information. Quality is equated with costs, and restriction rather than access is emphasized. The proposals to collect only that information which can be justified as cost effective immediately to the generating agency and to turn over to the private sector the dissemination of all information which appears to be profitable in the short run could have serious consequences for scientific research and communication in this country.

This trend is a dramatic reversal of the traditional partnership between the Federal Government and the Nation's research universities. Under the Federal Government depository system, universities have assumed the substantial financial responsibility for housing, preserving, and making accessible to all citizens the full range of Government publications in return for free deposit.

We have been compelled by regulation to provide access to Government documents in our libraries despite the fact free access to a private university library is not available to anyone else. The new policy proposes to give the same information, created at the taxpayer's expense, to the for-profit sector for resale to the citizenry and to withhold it from the universities.

The growth of the information technology industry and the intense international competition surrounding this industry has essentially split the scientific research community. The imperative to compete economically and militarily has created an enormous pressure for security and classification of basic research data. Research results from technological corporations as well as Government research centers are not being freely disseminated. University librarians are discovering that corporate sources are closed to our researchers while our libraries and data bases are used heavily by the corporations. In some instances, we are being called and asked to call other information to get information from them. The corporations will not exchange information among themselves.

The rapidly increasing demand for machine-readable information in the corporate sector has shifted the primary market for such information from the research university to the corporation with the consequence that the information industry is gearing its product to the private sector. The universities are in danger of being priced out of the market. One observer, a trustee of a large, private university, estimated recently that in the pharmaceutical industry, the proportionate corporate investment in information resources per employee is three times that of the university.

The financial burden on universities to provide the new capacities created by information technology is enormous. Not only must entire laboratories in all disciplines be retooled with increasingly sophisticated instrumentation, but the capital costs for installing state-of-the-art communications networks and equipping all students and faculty with computing capacity are simply beyond the financial capabilities of our large research universities. The recent corporate programs of large gifts of hardware to universities have received considerable publicity. The fact that each gift requires a matching contribution by the university for additional and specialized staff, software, networking capacity, and peripherals has been generally unrecognized. The rapid obsolescence of hardware and software creates replacement costs which are unprecedented in university budgets. The fact that the technology is supplemental rather than substitutional means that cost reallocations, at least during the short term, are not viable solutions. Increased productivity, saving of research time, and the improved quality of research do not generate revenue in a university budget.

Unimpeded access to research data and results is critical to the Nation's capacity to maintain leadership in science and technology. The realization of the potential benefits of information technology will require judicious policy decisions on a global scale with considerable Government support to insure equity of access and protection of our basic research enterprise from the immediate pressures of the marketplace. Many of us are very much concerned in 20 years it will not be possible to do substantive scientific research in the university.

Thank you.

[The prepared statement of Dr. Battin follows:]

U. S. House of Representatives
Committee on Science and Technology
Task Force on Science Policy
Hearing
September 12, 1985

My name is Patricia Battin. I am Vice President and University Librarian at Columbia University. I am honored to have the opportunity to discuss with you the concerns of research universities about our ability to provide the necessary quality of information services in the electronic age, and more specifically, access to machine-readable data bases and networks for scientists.

The capabilities of the new information technologies have had and will continue to have a fundamental and revolutionary impact on the manner in which academic research scientists acquire, use, and disseminate information. The capacity to organize and manipulate information in machine-readable format by sophisticated retrieval systems and the use of Boolean logic has stimulated different ways of thinking about and conceptualizing scientific inquiries. The graphics capability of computers makes possible the creation of three-dimensional models in machine-readable form, which then become important tools for related and continuing research efforts in other laboratories and universities. Communications technologies coupled with the widespread use of microcomputers now support rapid global transmission of research findings, numeric and quantitative data, and informal collegial communications among individual scientists. As one scientist has observed, "Digitized information has become a way of life."

However, this new way of life has outpaced our efforts to conceptualize, develop, and finance the new infra-structure necessary for the full and productive use of the new technologies, which require compatibilities of hardware, software, and network gateways on an international scale to meet the needs of the scientific research community. In addition to these organizational and policy barriers, the characteristics of information technology, which on the one hand permit an extraordinary expansion of the ability to create, store, and disseminate information, also encourage the chaotic proliferation of information resources and permit unprecedented control of access to that information. The ability to control access to information by charging a fee per use has serious implications for the individual researcher as well as the university's capacity to provide the necessary information services to support scientific research.

Since unfettered access to information sources and open communication of research results have been the hallmarks of American scientific inquiry and research productivity, I would like to focus my remarks on the new barriers to this traditional access accompanying the powerful potential of information technology. In addition, the emergence of an "information industry" which views information as a commodity rather than a public good is causing an alarming shift in the perception of value from the intellectual quality of information to a value based on short-term market demand.

Historically, the university has defined the responsibility for providing sources of information to faculty and students as a central function, mainly in the form of libraries. Once resources have been acquired by the university, they have been available as a free good for its members, by virtue of their appointment or their admission as students, and in the case of public institutions, society at large, including the corporate sector. Costs have been budgeted centrally and users have been charged little or, most commonly, nothing. Subsidized browsing--the capacity for broad access to information sources at no charge to the user--has been the primary characteristic of our scientific research enterprise.

Funding for computing, because of its magnitude and rapid growth, has been generally addressed in an ad hoc manner, and because initial uses of computing were not for information processing, cost recovery from the individual became the basic funding strategy. The rapid growth of computer and communications technology for information exchange among the community of scholars and in society at large has created a chaotic environment and rendered the traditional organizational structures obsolete.

Contrary to futuristic predictions, the electronic communication systems and capacities have supplemented, not supplanted, the traditional means of communication. The peer-reviewed scholarly journal remains the primary means of communicating scientific research results. There is no indication at present that scientists are prepared to accept electronic formats as a substitute for printed materials. The need for linkages between formats is paramount. The expansion of new information sources and tools creates incremental expenses for the university and requires a new information infra-structure to meet the demands of scientists, who want both books and data bases, libraries and electronic networks.

Chemical Abstracts represents a good paradigm of the present organizational chaos and the incremental costs of providing information services. At the present time, the University through the Libraries makes the printed copy available to students and faculty at no cost to the individual. *Chem Abstracts* is also available in machine-readable form through the library's institutional access or password. Typically, a reference librarian trained in the specific protocols performs the search for the client who pays the line charges and CPU costs. Now, researchers with personal computers want direct access to the data base from a variety of locations. The American Chemical Society does not have the capacity to accommodate the uncontrolled multitude of individual users, so in response to this need, ACS now provides an access arrangement which permits a small number of individual users to search the system during off-peak hours for a substantial discount. At Columbia, we estimate that we have made available to our faculty and graduate students about $75,000 worth of searching time for the annual $5,000 fee. There is no way our graduate students could have afforded this service without the licensing arrangement.

There are several significant points to be noted:

1) For the foreseeable future, an institution must provide all three types of access. One is not a substitute for the other:

--certain kinds of scholarly inquiry require the information capacities provided by the printed format

--there will always be students and faculty who require access to CAS but who are not sufficiently specialized to possess the skills for independent searching of the data base

--there will be a core of specialists with personal computers who require direct access

2) The costs are not substitutional but substantially incremental

3) The fragmentation of access to data bases in isimical to the academic purposes of the institution. Therefore, a centralized infra-structure is required to make sure that access to all available information sources is coordinated and provided on an institution-wide basis to eliminate the costs of redundancy.

4) The traditional procedures for allocation of costs and the control of expenditures have undergone a radical transformation.

The rapid increase of powerful microcomputers has expanded the dependency of scientists on new ways of manipulating, generating, recording and disseminating information through the use of data bases and networks. But the use of microcomputers has mushroomed far beyond the development of an affordable infra-structure to support the convenient and coordinated processing or research data and scientific knowledge. Our bibliographic and computer networks were designed to be mediated through centrally managed service organizations—libraries and computer centers--and their protocols reflect that design. Despite the sophisticated power of computers and telecommunications networks, the frustrations of incompatible hardware, software, and networks plus the lack of standardized protocols for organizing and retrieving information in machine-readable data bases lead most scientists to pick up the phone and call a colleague in their search for information. As one frustrated scientist reported, "Research today is 90% search and 10% research."

The following example illustrates the present chaos: A graduate student in a Columbia biology laboratory asked a reference librarian if she could find a table giving the complete protein sequence for E. coli RNA polymerase. She knew that the sequence had been completed in the last year and said that the work had been done by many different researchers who published their results in many different journals. She had also heard that the National Library of Medicine had a data base which might contain the answer.

Various books in the Biology Library supplied parts of the sequence, but not the whole sequence. Chemical Abstracts had many citations but not the actual data. Eventually, via the New York Academy of Medicine, the librarian made contact with a lab at the National Biomedical Research Foundation at Georgetown University. They had the sequence in a set of 7 tables which they would run off and send to Columbia. They also told her that the National Institutes of Health had just acquired the data bases and they would become public in several months. Up to that time, an individual had to make special arrangements for access. As it then turned out, after all these efforts, one researcher at the Cancer Research Center, College of Physicians and Surgeons, Columbia University, had such access, but no one else knew it.

A major concern among scientists is the lack of good software and compatible networks. The capacity to customize access is of paramount importance, and scientists stress that the avilable technology should be as adaptable and flexible as possible because use differs by discipline, by individual, and by the nature of the inquiry. Scientists emphasize the need to integrate all kinds of information on the individual electronic workstation: internal and external data bases, collegial internal and external communication networks, software, user assistance, consultation services, and the bility to share information easily. In sum, scientists want a variety of information and communication resources through one source and they want to be able to use it as easily as possible.

The current array of networks (BITNET, ARPANET, CSNET, NSFNET, OCLC, AND RLIN plus the commercial facilities) were designed to connect centrally managed computer hosts which had the capacity to direct traffic. The widespread use of microcomputers has placed the technology in the user's hands and created the need for a global telecommunications network accessible to all scholars with standardized gateways, file transfer capabilities, and comprehensive user directories. There is also a conflict between funding sources based on political and organizational jurisdictions and the scholarly need for access to the universe of knowledge regardless of location, format, or ownership. In addition, the magnitude of costs for capital investment in hardware, software, and networking equipment has added enormously to university budgets. The effectiveness of electronic dissemination is serious eroded unless everyone has convenient access. The proposed rise of A.T. and T. costs has created further barriers to access by encouraging the spread of locally owned and incompatible networks in universities and corporations.

The very valuable data bases constructed in numerous laboratories around the world are not readily available. Their existence is communicated generally through the invisible network because of the lack of compatible electronic networks and retrieval capacities. As a consequence, much development work is proceeding in parallel with a high cost of redundant effort and expenditure of resources. There is no publicly subsidized international network coordination for the scientific community.

An example of the frustration experienced by the scientific researcher is the following: a Columbia scientist has developed a data base of approximately 1,000 bibliographic citations in the field of animal intelligence. Most of these items are unique and not recorded anywhere else. At present, there exists no scholarly network through which he can make this information available to colleagues on a cost-recovery basis. The data base is too small and too specialized to attract commercial vendors, who are interested only in large-volume compilations.

It is unfortunately true that the information needs of the scientific research community run counter to the imperatives of the for-profit sector, which views information as a commodity to be bought and sold. That philosophy is in direct conflict with the belief that information is a public good and not amenable to the traditional value structure of the economic system.

The imperatives of the for-profit section -- maximized profits, short-term market demand, opposition to standards and compatibilities, and barriers to access imposed by competitive pressures -- present enormous obstacles to the continuation of our national tradition of private and public subsidization of an information infra-structure available to all citizens. The nation's research universities -- both public and private -- through their research libraries have combined with the federally supported Library of Congress, National Library of Medicine, and National Agriculture Library and state and local libraries across the nation to acquire, record, preserve, and make available this country's intellectual heritage, regardless of its imeediate economic value. There is no indication that the various commercial organizations marketing data bases and other information sources share these objectives, which are critical to our scientific community.

The traditional systems of peer review and quality control have not been adopted by most data base publishers. For example, there is serious and demonstrable concern about the quality of the numerical data bases. Many are very dirty, give no sources of their information, and access is very expensive.

A major concern for scientists is the continuation of the subsidized browsing capacity in the electronic environment. The control of data bases and networks by the for-profit sector has created a set of costs imposed directly on the information seeker. There is already evidence that this constraint influences the path of intellectual inquiry, the choice of research topics for the graduate student, and alarming variations in the level of potential productivity among the information haves and have-nots. Information costs have now become a visible influence in determining the thoroughness of a literature search by graduate students, a factor which erodes the overall quality of the research effort.

The recent OMB circular, "Management of Federal Information Resources," represents a significant change of government policy toward the provision of information. Quality is equated with costs, and restriction rather than access is emphasized. The proposals to collect only that information which can be justified as cost-effective immediately to the generating agency and to turn over to the private sector the dissemination of all information which appears to be profitable in the short run could have serious consequences for scientific research and communication in this country.

For example, several government agencies -- The Department of Agriculture, the Patent and Trademark Office, and the Environmental Protection Agency--turned over data bases of government information to private vendors. The EPA's Chemical Information System, twenty chemical data bases with physical and regulatory data, was divided and given to two private contractors. Users are concerned about cost and access to these data bases and about the possibility that unprofitable but scientifically valuable information might be dropped.

This trend is a dramatic reversal of the traditional partnership between the federal government and the nation's research universities. Under the federal government depository system, universities have assumed the substantial financial responsibility for housing, preserving and making accessible to all citizens the full range of government publications in return for free deposit. The new policy now proposes to give this same information, created at the taxpayer's expense, to the for-profit sector for re-sale to the citizenry and to withhold it from the universities.

The growth of the information technology industry and the intense international competition surrounding this industry has essentially split the scientific research community. The imperative to compete economically and militarily has created an enormous pressure for security and classification of basic research data. Research results from technological corporations as well as government research centers are not being freely disseminated. University librarians are discovering that corporate sources are closed to our researchers while our libraries and data bases are used heavily by the corporations.

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The financial burden on universities to provide the new capacities created by information technology is enormous. Not only must entire laboratories in all disciplines be re-tooled with increasingly sophisticated instrumentation, but the capital costs for installing state of the art communications networks and equipping all students and faculty with computing capacity are simply beyond the financial capabilities of our large research universities. The recent corporate programs of large gifts of hardware to universities have received considerable publicity. The fact that each gift requires a matching contribution by the university for additional and specialized staff, software, networking capacity, and peripherals has been generally unrecognized. The rapid obsolescence of hardware and software creates replacement costs which are unprecedented in university budgets. The fact that the technology is supplemental rather than subsitutional means that cost re-allocations, at least during the short term, are not viable solutions. Increased productivity, saving of research time, and the improved quality of research do not generate revenue in a university budget.

Unimpeded access to research data and results is critical to the nation's capacity to maintain leadership in science and technology. The realization of the potential benefits of information technology will require judicious policy decisions on a global scale with considerable government support to insure equity of access and protection of our basic research enterprise from the immediate pressures of the market place.

Mr. WALGREN. Thank you very much for that testimony. It is very challenging.

We turn now to Dr. Newell.

[A biographical sketch of Dr. Newell follows:]

DR. ALLEN NEWELL

U.A. and Helen Whitaker University Professor of Computer Science at Carnegie-Mellon University. Educated in physics (BS Stanford), mathematics (Princeton) and industrial administration (PhD Carnegie Institute of Technology, 1957). At the Rand Corporation before joining CMU in 1961. Have worked in both artificial intelligence and cognitive psychology since their emergence in the mid-fifties, mostly on problem solving and cognitive architectures, but also on list processing, computer architecture, human-computer interfaces and psychologically based models of human-computer interaction. Received the Harry Goode award of the American Federation of Information Processing Societies (AFIPS); (with Herbert A. Simon) the A.M. Turing Award of the Association of Computing Machinery; (with William C. Biel, Robert Chapman and John L. Kennedy) the 1979 Alexander C. Williams Jr. Award of the Human Factors Society and the 1985 Distinguished Research Contribution Award from the American Psychological Association. Member of the National Academy of Sciences and the National Academy of Engineering. Fellow of the IEEE and the AAAS, and member of other related professional societies. First president of the American Association for Artificial Intelligence (AAAI).

Mr. WALGREN. We turn now to Dr. Newell.

STATEMENT OF DR. ALLEN NEWELL, U.A. AND HELEN WHITAKER UNIVERSITY PROFESSOR OF COMPUTER SCIENCE, CARNEGIE-MELLON UNIVERSITY, PITTSBURGH, PA

Dr. NEWELL. I thought I would—there is no microphone. Will that present a problem to you?

Mr. WALGREN. No, if we project well, everybody will hear.

Dr. NEWELL. I am honored to be here. Dr. Ostenso, in talking to me, said that the main objective of these hearings was to try and help you understand the nature of these new technologies and the way they influence science, and I thought I would focus on what I think were sort of really big basic characterizations and hope there will be questions that would pick up and focus on parts of it.

Just so you know who I am, I am a computer scientist. I have a series of basic areas in artificial intelligence. In fact, I have written on networks, but I don't do research on networks, and I say that only because there is a particular article Bob Sproul and I did, which is widely read, about networks and I come forward with someone who has had a lot of experience with networks.

I am a member of DARPA Computer Science Research Community. In fact, one of the things I bring as a piece of experience is that I'm a member of a research class that has done that.

Let me start out with some rather general things, first, which I think are very important in trying to assess these new technologies, not just communication and networking and data bases, but all of them connected with the computer. I took this first statement out of a report that was presented, "Speed up by a billion in 45 years, cost down by $100 million." What that amounts to is a factor of 10 in power every 5 years, getting cheaper, of course. Now, that is the fact.

The important thing to understand about that is any time a factor of 10 changes, it is a new world, everything is different. And I tried to illustrate this by several ways because it is important to find a way of thinking of the world in terms of how big it is. So in terms of going across the country, here are factors of 10, going it in the month, 3 days, 8 hours and 50 minutes.

As we have seen—our society changes—we are now down to the 50 minutes yet. In fact, our world would be very different. Think what life would be like if you could move from reading a book in a month to reading it in 3 days to reading books every 8 hours to reading books every 50 minutes. If we could read books in 50 minutes, in fact, our entire world would be different.

I tried to think of one that might be sort of directly relevant to Congress. If Congress operated as it kind of does now, 3 months to get something through, if one could get a bill through, with all the discussions and everything, in 10 days or one day or in 2 hours, the entire factor role of legislation in our country would be extremely different.

All I am trying to do is illustrate you have to realize every 5 years is a factor of 10 years here, and it makes for a different world, a reflection on Dr. Battin's comment, we are retooling. This factor of 10 says we will be retooling in the next 5 years and the 5 years after that.

The other thing you have to know about new worlds which is very important for determining this field is in the new world, things are rough and full of troubles. Every time we change things by a factor of 10, there is a lot of new things we don't know how to do. In particular, all the software systems and so forth that we are building, one must realize that every 5 years, as the basic technology improves, they are in fact a whole new world of software, and we don't know how to do them well, so software systems never come out very well on top of this thing, although everything is getting better.

Let me now try to just make clear what computer communication is for science. The functions of communication in science, of course, just a raft of them, appending data, finding the results, plumbing the archives. Science is cumulative activity, and one communicates with other scientists and records in data bases and books to try and find out. Communication in science is infrastructure, and the most important thing about that is it is essential but can always be delayed.

And let me just give you an example. Many of you have had something to do with getting started, the NSF program in supercomputers, which in the appropriate wisdom that was put into that program, the building of a science net. From a scientist's point of view, there will be some of his research which he has to have that supercomputer for, and he will do almost anything to get it. He doesn't have to have the science net. He can always get in his car or take an airplane or do anything else and he can find a way to getting use to those cycles. When you talk to the scientist and give him his choice, do you want supercomputer cycles, more of those, or do you want a network? He always says, "We will build the infrastructure tomorrow, give me my supercomputer cycles today."

I think if there is anything that has to be understood about networking and these communication things, it is that they're infrastructure and are like bridges. We come from Pittsburgh, and we understand all about the maintenance of bridges and how it is very easy to let that go for 50 years before you attend to it. That is always a problem. You can delay investment in the infrastructure, but you pay prices for it which are usually heavy.

So the first key issue, then, is—well, the thing about infrastructure is it determines the style with which science gets done, and style is again not a critical thing, and it takes a long time to change it. A kind of example is that as people shift to living on computers, there's lots of little anecdotes they can tell you, but you don't see the big changes until time goes by, which means you have made the investment in that infrastructure, which then pays off slowly later, and I'll have a couple of examples of that later on.

The first key issue that you have to understand about networking, computer networking, is how much and how often can you do it? Again, I've utilized this factor of 10. It is an entirely different computer network for communication in science, if it takes a day to turn things around or an hour or a minute or 3 seconds or a third of a second or a 30th of a second, in fact, if I am down here, I am talking about video pictures, I can transmit pictures of things happening. If I am up here, it's kind of like what the mails used to be like. So these changes represent quite different networks.

The same is true about whether you can communicate only a sentence at a time, a paragraph, a few pages, a whole paper or a book, and networks differ. So when you say "But we have a network for doing 'X', we do in fact have an ARPANET for some part of the community," that doesn't define what the capability is, and that doesn't mean that you now have done it and don't have to do more of it later in order to, in fact, allow you to move along, where before I could communicate paragraphs, and now I can communicate books.

In fact, if you look at the kinds of things that are true of computer networks, if you go down here, at the low end, one talks about mail and bulletin boards and computer conferencing and so forth, that is the kind of thing most of the computer networks available do. If you talk about transferring modest files and documents back and forth, it takes more, most networks will not do that now, it is too heavy, there is too much flow. We move up to the transfer of systems, which takes even more capacity, and we move up—let me skip over this. You move to moving speech and imagery around, and there are no good networks around that permits that over any reasonable community.

The second issue is integration. It is a key feature of this, which is what will make it pervade the society as we go along, that when you get things in marine-readable form, you can process them with computers. A good example, trivial example, but most are trivial in the sense they are like a scientist trying to get one more little fact about a DNA sequence or something. Trivial in terms of great discoveries. It is a little thing that helps the science happen. If one has people across the country coauthoring papers, if one can process it, your word processors, the thing flows back and forth, people make their comments on it, people make more comments on it, that flows back; and the entire process of offering a paper becomes a very different activity than it was before.

The third key issue is the one that was already emphasized, is that networks are only—only work well when everybody is on them. It depends what kinds of communities get on these networks. All of those things are the key issues you have to attend to.

Now, let me—since, as I say, I am not really an expert in networks except that I have lived in this community for 15 years, let me then use my own experience to put some concrete things on the table. ARPANET is a nationwide network of 200 computers. It involves the DARPA research community and defense community by now. It does allow mail, it allows documents and system transfer. It also allows remote interaction. It does not have the capacity to allow speech and imagery to flow around on it. It simply isn't that powerful. In my own life, I essentially process about 20 percent messages a day. About half of my communication with my scientific colleagues is via these messages now, and that is true locally and remotely across the country. It doesn't make any difference. I can talk to my graduate students this way.

My biggest phone use—I was thinking of it in terms of this meeting today—my biggest phone use is to talk to people who don't have access to networks. I go back into this other mode. All of my administrative life I have is on the machine, and that makes a big style difference in my own scientific life, because I run on a 7-day-a-week, 24-hour-a-day, and I have access to the administrative structure of my life, and I guarantee you my secretary does not work 7 days a week, 24 hours a day. That turns out, in fact, to be a very big effect, but, again, it's infrastructure. It is not critical at one level, but it is what makes my life work as a scientist.

For various reasons I have a distributed research group on the west coast, in Stanford and a little piece of it in Mr. Brown's organization, back in Pittsburgh. The operation of that research depends on being able to transfer software systems and documents, not just mail, and in fact can communicate several times a day. That is what makes that research project work.

Incidentally, it's kind of interesting, remote interaction turns out to be not an important part of that. Let me just skip to this last point.

The most interesting thing that has happened to me now that I have been doing this for a dozen years is that my entire scientific memory is on a machine. It used to be my desk looked like Dr. Ostenso's. It's piled high with papers, but it turns out all those things I care about are stored in the machine in machine-readable form and not on scientific notes on paper. That is a major shift for me as a scientist.

It has happened slowly, and I couldn't live without being on the machine at all times. I spend about 8 hours a day every day of the week on the machine all my life. It really has become—if you provide—if the country provides this kind of thing we are talking about, a major shift in the style of operation, which increases, as I say, my own scientific productivity a lot.

I don't want to discuss these at the moment because there isn't time, but I wanted to indicate some of the factors, and if there are any members who would like to bring up and ask about these, we can talk about them. We are talking about good networking. That is a separate issue. Much depends upon everyone being on it. It is moving, in fact—I think partly for some reasons that were mentioned by Dr. Battin—moving much slower than in fact would be useful for the scientific community. I will make a remark on that in a moment.

Powerful workstations, these seem to be coming along. There is a question of accumulative software tools that have to be redone all the time as we move into these new regimes of power we're capable of. There are, in fact, more exotic technologies, like can you communicate with natural language, and when we will have speak recognition, which is quite a way down the pike. There is things that will happen when we get good networking, which I call activity scientific documents, what one shifts around are not things to be read but programs to be executed that one interacts with.

There will be things like expert systems that know the literature and can help you solving the kinds of problems. The only reason for putting those up is not that they are eminent, but they are the kinds of things one must point to if they try to say why the scientific community living with computers will turn out to be an entirely different style of scientific life than we now have.

Let me kind of summarize and let John Seely Brown get to the podium. If I understand the technology at all, I think it is inevitable computer communication will become pervasive. There is a factor in there of the power of doing it that will just make it happen. The only question is when. And I do believe that is the main issue, because it can be delayed always in favor of doing the thing that gives more direct immediate payoff.

Ultimately, science will become much more effective and it will relate to these new styles of operations that happen. ARPANET, the one I am familiar with, is a shining example of Government investment in infrastructure. That was established 20 years ago. It, in fact, has led the way in showing what might happen. It has been the conceptual thing that has moved the entire thing, held in place for 20 years.

One of the things that is a crying shame is that that is the best network around of any size for long-haul networks, and that is kind of incredible after 20 years. I do think it relates to the other forces in our society, and which has other networks have come along may have less capability than ARPANET.

The last point is that I think you have to understand that science networks are instruments of freedom, that is they promote free inquiry, and that is, in fact, a comparative advantage of the United States. I mean, it wasn't—it's not my intent at all to inject into any of this discussion the notion of competitive advantage with our brothers in the Soviet Union, but when I think about networks and how they will evolve and what they do to communities that have them, I get a real chuckle out of thinking about the Soviet Union being forced to move to network communities in order to get the scientific productivity out of it, because in fact these networks will force freedom of inquiry, and if the Soviets in fact try to narrow their networks carefully, they will find they do not get the advantage that comes from having a large community of scientists in free communication over the entire community.

Thank you.

[The prepared statement of Dr. Newell follows:]

Transparencies for Panel on Impact of Information Technologies on the Communication of Science

Hearings on the Impact of the Information Age on Science

Task Force on Science Policy
Committee on Science and Technology
US House of Representatives
1000:1200 12 Sep 85

Allen Newell
Carnegie-Mellon University

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TABLE OF CONTENTS

Who I am and what I can offer
General Trends to Keep Clear
Computer communication for science
Specific Experience as a Scientist
What is coming that affects scientific communication
On impacts and issues

WHO I AM AND WHAT I CAN OFFER

I am a computer scientist and a professor

My basic areas of research:

- Artificial intelligence (expert systems)
- Cognitive psychology (how people think)
- Human interaction with computers
- Computer architectures (for artificial intelligence)

I have written about (but don't do research in)

- Computer networking

Member DARPA computer-science research community

- Living on ARPANET for a dozen years

GENERAL TRENDS TO BE CLEAR ON

The device technology drives everything
"Speed up by a billion in 45 years
Cost down by one hundred million"
Factor of 10 in power every 5 years (& cheaper)

A factor of 10 is a new world — everything changes
Cross country: 1 month - 3 days - 8 hours - 50 min
Read a book: 1 month - 3 days - 8 hours - 50 min
Passing a bill: 3 months - 10 days - 1 day - 2 hours

In a new world, things are rough and full of troubles
Humans not do things right the first time — we learn
Software & systems have troubles — always new

Takes a long time to make a major research gain
And you must pay attention to it
Speech recognition by computers

1950-55	Instrumentation for speech
1955-60	Recognition by analog devices
1960-65	Little attention
1965-70	Little attention
1970-75	First continuous speech push (DARPA)
1975-80	Commercial isolated recognizers only
1980-85	Little attention
1985-90	[Second continuous speech push]
1990-95	[Beginning applications]
1995-00	[Massive applications]

COMPUTER COMMUNICATION FOR SCIENCE

1. Functions of communication in science
    Obtain data, tell results, find new problems, plumb archive

2. Communication in science is infrastructure
    May be essential, but is seldom critical
    Example: Supercomputers vs Science Net

3. Infrastructure determines styles of operating
    Styles are not critical, take a long time to emerge
    Example: The shift to living on line to a computer

4. First key issue: How much and how often
1 day - 1 hr - 5 min - 30 sec - 3 sec - 1/3 sec - 1/30 sec
1 sentence - 1 paragraph - 2 pages - 1 paper - 1 book

5. Functions of computer communication
    Mail, Bulletin boards, computer conferencing
    Transfer of modest files and documents
    Transfer of systems
    Remote (modest) interaction
    Remote (high speed) interaction
    Transfer of speech and imagery

6. Second key issue: Integration
    Computer can process what is communicated
    Example: Distant coauthoring of a joint paper

7. Third key issue: Many must be on a network

SPECIFIC EXPERIENCE AS A SCIENTIST

- Have been on ARPANET since early 1970s
    - ARPANET is nationwide network of computers (200)
        - DARPA research community, defense community
    - Mail, document & system transfer, remote interaction

- Do all my scientific work from home, using computer
    - 10 chars/sec - 100 chars/sec - 1000 chars/sec -

- Do about twenty personal messages a day
    - Over half of communication to colleagues
        - Both local and remote
    - Biggest phone use is to those without networking
    - Large fraction of administration on line
        - Secretary and I jointly, around the clock

- Distributed research group on West Coast & Pittsburgh
    - Transfer of software systems essential
    - Transfer of documents is essential
    - Remote interaction is not

- Heavy use goes in bursts

- All scientific documents created on line
    - And passed around as modifiable files

- My scientific memory is in computer, not on paper
    - Eight hours per day on computer

WHAT IS COMING THAT MIGHT AFFECT SCIENTIFIC COMMUNICATION

Good networking
    Much depends on everyone being on it
    Moving slower than is useful

Powerful workstations
    These seem to be coming along adquately

Cumulative software tools

Natural language comprehension
    Moved into a positive phase again

Speech recognition
    Requires much long term pushing

Active scientific documents
    Barely started, but will be a major shift in style

Expert systems that know the literature
    Not started yet, though other work preparing way

ON IMPACTS AND ISSUES

1. Computer communication will become pervasive

    The only question is when

    Can be delayed, because it is infrastructure

        But then you pay the price — opportunity

2. Science will come to operate more effectively

    Ultimately much more effectively

    New styles of operation

3. ARPANET is a shining example of government investment in infrastructure

    It has led the way in showing what might happen

    It has been held in place for almost twenty years

    Still is the best network around — which is a shame

4. Science networks are instruments of freedom

    Networks promote freedom of inquiry

    USA comparative advantage

GENERAL TRENDS TO BE CLEAR ON

The device technology drives everything

"Speed up by a billion in 45 years

Cost down by one hundred million"

Factor of 10 in power every 5 years (& cheaper)

A factor of 10 is a new world — everything changes

Cross country: 1 month - 3 days - 8 hours - 50 min

Read a book: 1 month - 3 days - 8 hours - 50 min

Passing a bill: 3 months - 10 days - 1 day - 2 hours

In a new world, things are rough and full of troubles

Humans not do things right the first time — we learn

Software & systems have troubles — always new

GENERAL TRENDS TO BE CLEAR ON (2)

Takes a long time to make a major research gain

And you must pay attention to it

Speech recognition by computers

1950-55	Instrumentation for speech
1955-60	Recognition by analog devices
1960-65	Little attention
1965-70	Little attention
1970-75	First continuous speech push (DARPA)
1975-80	Commercial isolated recognizers only
1980-85	Little attention
1985-90	[Second continuous speech push]
1990-95	[Beginning applications]
1995-00	[Massive applications]

Mr. **Walgren**. Thank you very much for that.
Let's turn, then, to Dr. John Seely Brown.

STATEMENT OF DR. JOHN SEELY BROWN, PRINCIPAL SCIENTIST AND DIRECTOR, INTELLIGENCE SYSTEMS LABORATORY, XEROX PALO ALTO RESEARCH CENTER, PALO ALTO, CA

Dr. **Brown**. Thank you. I shall be brief and informal. I now know why, because actually Allen Newell basically said everything I was going to say in terms of providing background information, what it is like to live in the information age and the experiences forthcoming from that, and also where technology is really going.

One of the examples I had in mind about how rapidly technology is moving and how that challenges our usual notions of infrastructure had to do with what has happened in the automobile if Detroit had moved ahead as fast as information technology. Thinking about having a car in the last 10 years would have improved to the point of having cars doing something like 1,000 miles an hour, fuel consumption of 200 miles to the gallon. An interesting thing about that comparison is, think what that means to driver training, safety programs, think what that would mean to the interstate highway program if, in fact, technology of automobiles moved ahead that rapidly. What I am suggesting is that same analogy came back to the information technologies, and we have to be thinking about that in terms of the issues you brought up earlier.

Basically, as the final wrap-up witness, I wanted to direct some comments on the information age as it impacts both the conduct and communication of sciences, although I realize this hearing today has been focusing primarily on the latter one. What I want to do first is describe how informational terms are helping us cope with the ever-increasing complexity of doing science, of science itself, then stop back and reflect a moment on the experiences that I have lived through for the last decade, having lived in an environment that had electronic mail, extraordinarily personnel work stations, powerful main frames, and likewise software environments that allowed us to do rapid prototyping of complex systems. In that environment, I want to reflect a little bit on the tools that have enabled our ability to communicate and deliberate with each other. I want to focus on that collaboration component. I think there are some nonobvious reasons that come up in that context.

Finally, I will step back and focus attention on some critical issues I think deserve our special attention, information tools to help us cope with the complexity of science. Let me reflect on that briefly both from the point of view of the experimentalists and the theorists, two quite separate activities. These activities are being brought closer and closer together with the rise of computational science by computational physics that does an interesting job of bridging these two diverse kinds of investigations—tools that help the experimentalists. The thing that is slightly interesting on that horizon is a notion of smart instruments, instruments connected to experimental setups that on their own are capable of analyzing data streaming through, looking for patterns in that data and making decisions about how to change in subtle ways the experimental setup, likewise, the beginning appearance of expert systems that help the experimentalists interpret the data of his experiment, for example, finding complex structures and so on coming out of various instruments.

In terms of the theoritician, one of the kinds of unusual tools coming on the surface right now are tools to help the theorist keep track of incredibly complex arguments. Basically, think about the problem of constructing an argument that involves hundreds, if not thousands, of interrelated hypothesis, arguments, counter-arguments, arguments, counter-arguments, arguments to the counter-arguments and so on, much like an informal mathematical proof, but one that grows and grows. What we are beginning to see, a new class of tools that helps in the informal thinking processes that go into the structuring of complex arguments that is going to be necessary to cope with the problems theoreticians are trying to tackle. In fact, I find one of the interesting issues coming up in the information age is the fact that informational technologies are opening up brand new studies, brand new areas of investigation.

For example, the area that both Allen Newell and I spent a lot of time on has to do with the fact that now, perhaps for the first time, we actually have new ways to penetrate how the human mind works, mental processes, how knowledge is structured in the human mind, how it is represented, how it is used. How do we look at those things? Basically, in the past, we were restricted if we were trying to build precise theories reflecting on the use of mathematical models, but, in fact, the computer has provided us a framework of language, of mental language, if you wish, for structuring precise theories about processes, mental processes, enabling us to penetrate the unobservable by constructing these models and running them on the computer in order to understand their talents. So, basically, the information age is in fact opening up whole new arenas of investigation that were previously, perhaps, even unprofitable but now we can bring the level of scientific precision that heretofore was at least impossible.

Let me move on now to the question of information tools that enhance our ability to collaborate and communicate. The most obvious, the one Allen has already talked about, is the notion of electronic mail. Electronic mail has some interesting properties. It is not an interruptive device like the telephone, it has archival properties, it has a relative informality that is much less than a letter or scientific paper and has very fast turnaround. Interestingly, with the electronic mail, we can now form inner circles of research collaboration based now purely on intellectual overlaps of interests and not have to consider geographic constraints. This means for the first time you really can find small groups of people spread around the country, as your group actually represent in our lab in Pittsburgh, that have a truly shared intellectual interest and can work together a common problem, no matter where we are in the country as long as we have the appropriate infrastructure.

One of the kinds of surprising things that has come out of our experiences of using electronic mail stems from something as trivial as the response time we have in getting comments on not only ideas, but comments on initial drafts of papers. Now, of course, it is nice to be able to get a fast response to a draft of a paper, but what actually turns out to happen is we can watch the evolution of an idea, an evolution of a paper take place before us, looking at articles that get revised, revised, revised in response to criticisms, comments and so on, and by watching the evolutionary process of a paper or an idea, we get a much deeper insight into how our colleague is actually thinking. So, in fact, electronic infrastructure like this provides a new insight to help us penetrate deeper into the content of what our colleague is actually thinking and saying.

I think we all know it is hard to pick up a brand new paper and understand what the gut intuitions are of the working scientist, but if you could have seen how that paper evolved over like even 2 or 3 weeks, you get a much better indication of how that person is thinking, what he or she finds critical and so on. Likewise, with an ocean of distribution nets, distribution lists in electronic mail or community bulletin boards, where you can expand your inner circle of colleagues to include new groups of people that you want to watch kind of casual interactions on, I have found one of the surprising things that have come up from these community bulletin boards, or these distribution list mechanisms that create a distribution list of people who have a more broadly shared intellectual interest, is the fact of a new kind of serendipity, a kind of serendipity we're apt to look in electronic document schemes.

A lot of times I get a lot of ideas walking through the shelves in a library. What is going to replace that accidental discovery of something in the electronic world? Often by just watching the kind of interactions going on on a community bullentin board. Although I am not primarily interested in that particular subtopic being argued today, often by watching that unfold, an idea will come out that has to do with a completely different problem I happen to be working on, but I see how this person's argument could be slightly generalized to handle the problem I am thinking about. In fact, these new electronic infrastructures have interesting aspects of serendipity built into them I think we have tended to overlook.

Finally, the area that fascinates me the most and one we're just beginning to focus more and more attention on is the very notion of tools to enhance our ability to collaborate in small groups of people, even in a particular meeting room like this. The question is, how do we use the informational tools to radicalize our ability to be able to collaboratively brainstorm, problem solve, coauthorship, design experiments and so on? Can we actually use these tools to actually make collaboration more effective and perhaps find ways to tap the creativity that's inherent in the group potential that way?

One of the things that has surprised me—we have been experimenting in the last year or two on some beginning tools to do this—is the way these tools can lead to a knowledge base concerning the practice of science. Let me give an example. Suppose you wanted to design a complex experiment today in physics, biology, electrical engineering, or even computer design, in my particular case. Very often in that design process there are literally 1,000 decisions, at least 1,000 decisions that get made. Each decision supports arguments, counter-arguments, counter-counter-arguments done by a small design team. In that argumentation that goes on, all kinds of implicit assumptions often get revealed and then lost. In fact, often what happens is at the end of a major design, basically, you roll out a product or an experiment, and the result of your efforts is a product. Now, that product of that experiment gets run, gets debugged and so on. In that debugging process, some of the underlying assumptions, arguments, et cetera, can get refined, supported and so on. Now, interestingly, it's after you get it all done, by and large, what happens is that all that is kept track of is the conclusion. And yet in the process of constructing this experiment, in running this experiment, a tremendous amount of other knowledge concerning the refinement of the practice of doing science that underlays those types of decisions gets refined, and then lost.

So what I find interesting is how these electronic tools are beginning to provide ways to capture this knowledge underlying the processes of doing something and through that setting the stages for building, if you wish, knowledge bases as opposed to just data bases, knowledge bases about, for example, the procedures to carry out certain types of experimental steps, interestingly hidden assumptions about those procedures and so on, very much like the notion of knowledge bases underlying expert systems. In fact, what I am beginning to see is through these tools to be able to get at the processes underlying conclusions like this is almost like a knowledge acquisition phase, very much like that, having to do with the construction of expert systems. So what I see happening now is by building tools that enhance our ability to collaborate effectively in small groups, by capturing that electronically, being able to structure that, that sets the beginning of a new kind of knowledge base that likewise will feed into and be able to be utilized by, we hope, relatively simple expert systems later on. So a new kind of infrastructure is being put in place, could be put in place by this new kind of collaborative problem-solving tool, set of tools. Fine.

Let me wrap up by talking about a couple of issues I think we should be sensitive to. One, of course, has to do with the classic problem of the capitalization of the information age itself. I am sure you have heard all too much about the problems of needing very expensive computational facilities. My part in this problem is only this, that we have to be sure to put in place mechanisms that understand the rapid advancement of this technology. That is to say very likely in terms of Allen's analogy earlier, the actual life cycle of some of the informational technology might only be 2 or 3 years, and yet we may be depreciating it over a 5-year schedule. That brings in some new problems we want to be sensitive to.

The second has to do with basically the problems of infrastructure, the topic that has cut across all three of our presentations this morning. One cautionary note is that it is all too easy to say in order to expedite infrastructures, we want to nail down standards. However, just like Allen said, look at how rapidly technology is advancing. The real intellectual challenge we have is how to put in place standards, standards of communication, protocols, standards of kinds of programming languages so we can capitalize on each other's software base and so forth, put in place standards that have built into them the mechanism of change.

How do you standardize something but standardize it in a way that enables it to grow with you or for you? I think that is quite a different type of problem. We're beginning to see this level in the arena of standardization of programming languages.

Last, I want to stress that, in fact, although you have heard all of the romantic and not-so-romantic capabilities of the information age, it is my belief that surprisingly enough, we are really lacking a thorough, good, scientific foundation for even what information is. We have very little handle at a scientifically respectable or theoretical perspective on what the meaning of information is, of what the context of a message really is. Yet if we want to build good access systems to some of these electronic data bases, we're going to be able to need to be able to establish much better ways to talk about and formalize the content of information, we want to be able to have tools that manipulate the content of documents not just their form. And we want those tools not to be as ad hoc as current-day tools are, essentially tools such as expert systems.

Finally, in that same spirit, I think we ought to be aware we're just at the tip of the iceberg in the sense that for about 20 years we have been advancing along one notion of computation basically governed by the binomial architectural schemes. In the last few years, the field is blossoming open. In fact, we now recognize there can be thousands and thousands of new kinds of architectures that need to be explored. I think we have to understand that for the next 10 years we have to be sensitive to the diversity of this exploration and make sure we don't get prematurely locked in on just a few traditional ways to look at this technology.

I want to end by one slide. It is actually a slightly changed quote of T.S. Eriot. Let me put it up. I shall also read it for those who can't see it, something I think we should keep in mind as we are trying to find the real value of the information age: "Where is the wisdom we have lost in the knowledge? Where is the knowledge we have lost in the information?" And my slight addition: "Where is the information we have lost in the data?" We must try to keep separate information, data, knowledge, and wisdom.

Thank you.

[The prepared statement of Dr. Brown follows:]

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Draft: September 18, 1985

The Impact of the Information Age
On the Conduct and Communication of Science

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Introduction

That information systems are transforming scientfic research is almost a cliche. Some examples of technology's impact on science are well-known: the use of supercomputers in physics research; development of expert systems for medical diagnosis and geological analysis; use of computer networks and electronic databases for the spread of scientific knowledge. Less well known are the ways in which recent developments in information technology are enabling new forms of scientific collaboration and communication, providing the basis for new kinds of "intelligent" scientific instruments, and even spawning new scientific methods. We need to understand the nature and implications of these changes, and the ways in which emerging systems can augment the creative American scientific spirit.

Two aspects of the development and use of information technology in science are crucially important to recognize if we are to preserve our competitive edge not only in the information sciences themselves, but in all domains of scientific research. One is the sheer rapidity of advancements being made in the technology base -- computational processing power and memory -- underlying the information age, and the likelihood that the current pace of development will continue during the next decade. The second is that we stand at the threshold of major new developments in computer architectures, the direction of which will have a profound impact on the effectiveness of information technology in future scientific research.

These are exciting developments, holding much promise for the advance of scientific knowledge and its application to our personal and national well-being. But to capitalize on the potential power of these advances may require some rethinking of current funding practices in order to ensure that we remain competitive in expanding the frontiers of information technology and its use in science. We face four major challenges in attempting to optimize our progress: 1) to ensure adequate, and more crucially, ongoing capitalization of scientific information systems; 2) to develop a well-grounded theory of information (a theory of content or meaning) in order to guide the development of more flexible and "intelligent" information systems; and, perhaps most importantly, 3) to ensure the creation of appropriate infrastructures and the management of infrastructural change.

Before discussing these challenges, however, let us first consider the general impact that information technology is having on scientific research and the ways in which the nature of that impact may change as we progress in the information age.

Changes on the Horizon

New schemes for human-machine interfaces. One of the most fundamental (and to me exciting) changes currently transpiring in the information sciences is a direct result of the phenomenal growth of gross computing power. The plummeting cost of microprocessors and memory means that we can afford to put much more emphasis on what we information scientists call the "front end" of computational systems. Computing power has reached a performance/cost threshold that allows us to build more natural, less intimidating interfaces for communication between human and machine. For the first time it is possible to develop information systems that have more the properties of an intelligent lab assistant and less those of a myopic automaton.

What does this mean for scientific research? Earlier systems, constrained by limited computing cycles, provided little or no aid to their users in moving between the internal representation of data in the computer, and the presentation of data and data analyses in human scientific terms. Scientists often required considerable expertise in computer science as well as their own discipline, in order to make the necessary translations and to determine to what sorts of problems a given computational tool could be usefully applied.

A new generation of scientific workstations and current research into human-machine interfaces have two major aims. The first is to provide access to underlying computational resources while preserving the scientist's ability to think about scientific problems in the abstractions and technical terms of the domain itself. Interfaces to number-crunching engines (such as supercomputers) and databases, whether in the form of an integrated interface or an independent workstation, are being designed to act as intermediary between the scientist and the programmatic constructs in which these systems normally traffic. These efforts will entail, among other things, finding ways to project data in forms that tap human preceptual mechanisms and that allow the scientist to see the data's overall structure relative to the task at hand.

A second, and more ambitious, goal of current research is to develop intelligent interfaces that might act as a sort of scientific assistant, technical librarian or other helper. Such systems should be capable of advising a scientist on the appropriateness of using a particular computational tool for a given analysis, or of aiding a scientist in finding information that he does not know how to specify but that is relevant to his current problem. Expert system interfaces for scientific workstations will be expert not only in the idiosyncracies of the underlying computation tools and information sources, but also in the presuppositions and assumptions of the theories on which the tools are based.

These developments will have important repercussions for scientific research, not only rendering the scientific use of information technology far more productive, but leading to an ever greater penetration of technology into the conduct and communication of science.

Changes in the scientific enterprise. Information technology is providing new scientific tools for the conduct of both experimental and theoretical work in science. These tools not only reduce drudgery and increase efficiency; often they make possible new kinds of scientific research, such as more complex experiments or new paradigms for verifying scientific theories. What is more, these tools are beginning to effect subtle changes in our very conception of the scientific enterprise.

Traditionally, most scientific disciplines have supported a relatively clear dichotomy between experimental and theoretical work. Due to advances in computation, changes are underway in each of these subdomains. Experimentalists now have instruments that can analyze incoming data in real time and adjust the experimental parameters on the basis of the analysis.

Likewise, theoreticians can use information systems to assist in solving complex numerical or symbolic equations on which a theory is being based. Theory formation tools can also help manage theoretical analyses and informal proofs involving hundreds or even thousands of interrelated hypotheses. Such systems can keep track of alternative hypotheses, the evidence for and against them, and the assumptions underlying each line of argument, thereby aiding the scientist in the crucial task of scientific reasoning about incredibly complex phenomena -- phenomena that in the past have defied classical methods of proof and analysis. The availability of such tools leads to new theoretical methodologies appropriate to particular problems or domains. Competitive argumentation is such a methodology, developed by cognitive theorists to handle theory development in a domain in which the phenomena of interest cannot be observed directly but must be inferred.

However, computational advances have not led solely to changes in experimental work on the one hand and theoretical work on the other. From the scientific use of sophisticated simulation technology is emerging a new kind of hybrid activity in which experimentation and theorization are much more closely linked. Computational experimentation using simulation models of complex phenomena enables much finer control over experimental parameters and allows testing of effects that would be too expensive if done in nature.

For example, in physics we are seeing increasing use of computational studies of massively nonlinear or chaotic systems, such as the onset of turbulence in laminar flow. And in psychology we are witnessing the growth of radically new kinds of theories concerning how we acquire, structure, and use information and knowledge. In the latter case, not only have informational technologies provided powerful languages for framing theories of mental processes with a new level of precision, but they have also enabled researchers to "observe" the inner workings of the human mind by first postulating precise computational models of mental processes and then running those models to observe their entailments. (Interestingly, this emerging science of the mind, which depends directly on computational tools, is likely to suggest important directions for the development of new kinds of architectures for tomorrow's massively parallel symbolic processors -- i.e., super computers for symbolic computation.)

Changes in scientific communication. Perhaps one of the most intriguing influences of the information age concerns the relationship between the conduct and the communication of science. We already have in place sophisticated information infrastructures that facilitate the sharing of scientific knowledge across disciplines and across geographical distance. Electronic mail and electronic bulletin boards, whose development was spurred by DARPA's pioneering work on computer networks, have already had a substantial impact on both the practice and the sociology of computer science, the cognitive sciences and the field of artificial intelligence. With electronic mail reaching its tentacles into research laboratories all over the country, individual scientists are now able to establish collaborative working relationships based on intellectual rather than physical proximity.

Electronic mail, often augmented by distribution lists for individuals with shared intellectual interests, has also offered a new way to tap diversity of opinion in science. For the first time in scientific history, it is possible to pose a problem or issue a preliminary report to a geographically dispersed scientific community and to get feedback from many points of view *quickly*. Not only can such feedback help to pinpoint ambiguities and oversights in one's analyses, conjectures or theories, it can also help uncover potential conceptual flaws that are more obvious to researchers looking at the problem from somewhat different points of view. In a sense then, electronic mail, accompanied by an appropriate sociology, can make available on a more informal and ad hoc basis the intellectual resources institutionalized in the peer review process or annual technical meetings.

Electronic mail taps some of the advantages of conversation (speed of response) as well as some of the advantages of written material (widespread dissemination, opportunity to reflect on one's own or others' ideas, convenience to diverse schedules) to create a new medium for the interchange of ideas within the scientific community. However, I believe it is important not to stop there. Existing communication systems provide a base, technologically and experientially, upon which to build in order to further enhance our ability to tap the creative and analytic potential of scientific communities.

One of the crucial problems of increasing specialization in the sciences (and elsewhere) is the need for effective communication between individuals and subgroups and for preserving group knowledge over time and across projects. For example, even within relatively small, cohesive research groups, the need looms large for collaborative problem-solving, collaborative writing, and group brainstorming. Communication problems are exacerbated in interdisciplinary groups, yet many of the intellectual issues facing us in information science, the social sciences, and the cognitive sciences require interdisciplinary work. Appropriately designed tools to enhance collaboration through the sharing of files, the structuring and archiving of group interactions, online editing and annotation of documents and so on, are sorely needed. Interestingly, seen as a research problem, technological support of collaboration is just the sort of area that requires interdiscplinary scientific work: not only the technical but the sociological aspects of the problems require a deeper understanding than we currently have. However, I believe that research in this area can yield impressive results in terms of increased intellectual productivity.

Challenges and Pitfalls

Following is the set of concerns and challenges we must address if we are to maintain our competitive edge in the development and use of information technologies in the service of science.

Ongoing capitalization of equipment for scientific research. A common misconception is that because computers are growing cheaper no special attention needs to be given to capitalizing computers and workstations in our research laboratories. Quite to the contrary, I believe that one of our greatest challenges is to develop mechanisms not only for initial capitalization of computational and informational environments for the basic researcher, but equally important, to ensure that capitalization of equipment is not treated as a one-shot affair. As we discussed in the beginning of this paper, the rate of advancements in information technologies shows no sign of abatement. As a result, systems considered state-of-the-art today may well be obsolete three years from now -- a period far shorter than the standard depreciation cycle for most research equipment. If we are to provide the support for basic research that is necessary to maintain our competitive advantage in scientific innovation, we must ensure that informational technologies can be renewed or replaced at a rate that is commensurate with the life cycle of the equipment, no matter how short that may turn out to be.

What is required for equipping scientists with appropriate information technology? First, we must provide workstations and software capable of mediating between the idioms and abstractions of scientific thought and the programmatic abstractions employed by current supercomputers and mainframes. Further, while today's supercomputers generate data at a prodigious rate, that data must be interpreted by the scientist. Displaying the data in a way that aids the researcher in discovering its structure or meaning may require high-quality and powerful graphic displays. In short, serious scientific computing systems are needed both as backend number crunchers and as personal scientific workstations -- neither of which are inexpensive.

I should emphasize here that the need to provide researchers with state-of-the-art computational capabilities need not always entail junking older equipment, such as existing mainframes and supercomputers. As the science of human-machine interface design progresses, it should become possible to develop or update personal scientific workstations to act as flexible intermediaries between scientists and the powerful, if rigid, mainframe computating engines and databases. Such development strategies will enable us to preserve and leverage off existing resources.

Another aspect of capitalization has to do with the need to establish a critical mass in the distribution and use of information technology in scientfic research. In order to realize the potential of the information age for the advance of scientific discovery, we must use technology to build information and communications infrastructures. Almost by definition, such infrastructures cannot be built piecemeal. The use of telephones by a few individuals does little to enable a new kind of communication scenario. Not until nearly everyone has a telephone does the technology's real power become apparent. The same is true for workstations, networks, and databases. Nearly all research scientists need access to these devices for the advantages to scientific communication to emerge.

A science of information for the information age. Even given our limited experience with large-scale documents and databases, electronic message systems, and electronic bulletin boards, it is clear that we are on the brink of an information explosion. Although advances in optical disk technologies and symbolic computing provide the technological basis for coping with this explosion, technology constitutes but a small part of a satisfactory solution.

Foundations for information access and manipulation. What is crucially needed is the scientific basis that will enable us to move beyond rigid, ad hoc software systems for accessing data to a new generation of systems able to manage the *content* rather than the form of information. We need theories that explain how to extract and represent the meaning of information in much the same way that an human being does in reading a piece of text. Such theories would enable us to search, filter, and distribute messages based on the content of the message text rather than on the limited categorization in the subject field. Similarly, we would be able to search for and retrieve documents from gigantic document bases that have the content we require rather than a seemingly appropriate slot in an indexing scheme.

Foundations for scientific software. Equally problematic is the lack of a theoretical basis for extensible and easily modifiable software. That there is a software crisis is well understood, as is the fact that the total cost of information systems increasingly will be dominated by software development costs, What is often overlooked, however, is the consequences of rigid software for the conduct of science. Already we find our work habits determined by software systems that appear as large, unmanageable and impenetrable black boxes that cannot be changed or tinkered with. However, rendering this scientific software into a more transparent form is extremely problematic. We need a better theoretical understanding of how to construct transparent extensible systems in the first place. In the case of documents and databases, what is lacking is the theoretical foundation for representing and manipulating program content.

Of course, current expert systems attempt to provide "intelligent" front ends to databases and complex scientific tools. Impressive as these systems are, they are inherently restrictive and cannot be generalized to handle the rich kind of information access that will be needed in the near future. Nor are they likely to evolve into the requisite systems unless a considerably more ambitious effort is launched to solve a set of perplexing theoretical issues. These issues include such broad areas as what information/knowledge is, how its meaning emerges from its form, and what kinds of architectures will enable us more readily to build systems that can extract and operate on information content. Given the breadth and nature of these problems, developing a science of information will require a cross-disciplinary effort, that is, basic research spanning such diverse fields as linguistics, logic, psychology, computer science and artificial intelligence.

Computer architectures. An important dimension of any applied science of information will be the development of new computer architectures. Without belaboring the point, let me say that in the last few years the computer science community has begun to explore radically new kinds of computer architecture. These architectures break with the traditional von Neumann architectures as a step toward achieving effective, massively parallel computation -- computational schemes more akin to the human brain than to a desk-top calculator.

These new architectures hold the promise of revolutionizing certain kinds of computational practice both for numeric computation and for the symbolic computation that is more pertinent to expert systems development. But the realm of possible approaches to architecture and related software issues is immense. At this early stage we must guarantee that a diversity of explorations is pursued and that we avoid limiting our vision to currently held beliefs and practices in computation.

Discovering radical new architectures for a class of scientific problems can provide phenomenal leverage in terms of both cost and performance. If we as a nation are to preserve our lead in information technology and scientific innovation, it is imperative that we not overlook new computational schemes, which, albeit developed for highly specialized problems, may obsolete current architectures. In order to increase the probability of such developments, support for computer science research should not rest primarily in the hands of DARPA. Instead, research should be aggressively pursued through several funding channels and on several intellectual fronts, fronts that clearly include, but also transcend, the more traditional computer science research communities.

Creating infrastructures and managing infrastructural change. In the form of individual workstations and small local area networks, information technologies can clearly amplify the research effectiveness and collaborative capabilities of scientists. However, as we have emphasized elsewhere, the real potential of the information age for scientific research rests with our ability to establish the right kinds of technological, informational and communications infrastructures for use by the scientific community at large. These infrastructures are necessary not only to disseminate the fruits of past research, but also to expedite ongoing efforts. Let us consider several examples of the types and importance of infrastructures for effective development and use of information technology in science.

Electronic knowledge bases -- infrastructures for accessing and using scientific knowledge. Earlier we emphasized the importance of online access to information sources such as library catalogs and scientific databases. Equally important is the development and effective use of scientific knowledge bases. Properly designed, electronic knowledge bases could serve as powerful repositories of knowledge in forms to be accessed and used directly by smart computer programs running on an individual scientific workstation. For example, a knowledge base for recombinant DNA research might contain descriptors of relevant properties of DNA and enzymes, along with principles for synthesizing recombinant DNA structures. When directed by the scientist to simulate various syntheses, say for a particular effect, the smart workstation software would access the knowledge base, select the appropriate data, and carry out the synthesis.

The establishment of large-scale, nationally available knowledge bases, together with the development of appropriate workstation software, would help to create a new kind of knowledge infrastructure to support scientific research. At present the sharing of knowledge depends on the existence of, or access to, social/intellectual networks among human scientists. Knowledge base technology could help create supplementary infrastructures for sharing knowledge between computing systems, systems that could make use of remote knowledge without its first being interpreted by the scientist.

Social and technical infrastructures for sharing capital-intensive tools and processes. Appropriately designed infrastructures can help not only to disseminate knowledge but also to provide new kinds of learning and bootstrapping environments by providing access to precious, capital-intensive tools. A provocative example of a successful infrastructure created for this purpose is the Moses system in operation at the Information Science Institute at the University of Southern California.

Moses is a system for "telemanufacturing" the VLSI designs of students and faculty around the country, which uses the DARPA network to submit designs electronically for the capital-intensive mask-making and chip manufacturing processes. The system has several important qualities that help facilitate learning of VLSI design among students and specialists in other fields. First, Moses separates and fully specifies the knowledge required for design and fabrication of VLSI chips, incorporating a translation interface for communication between the two knowledge bases. The interface provides designers with a set of design constraints and protocols that can be interpreted into various fabrication processes.

Because Moses separates the principles for chip design from the extensive technical knowledge required for chip fabrication, communities of people who lack the requisite technical background are able to get involved in design. For example, an expert computer graphics person is able to apply his domain knowledge to the design of a special-purpose VLSI chip for a graphics workstation, without the investment required to learn about the fabrication process. This is important because reduction of the cost of entry could be one method of reducing overall design costs, while ensuring that fresh insights will be brought to bear on design issues.

Another feature of Moses is its use of space on the silicon wafers that encode chip designs. Traditionally each wafer contains many copies of the same chip. Moses enables multiple small designs, each submitted by a different designer, to be assembled and layed out on a single wafer, thereby reducing the cost of manufacturing any give design. Traditional methods generally constrain designers to concentrate on development of general-purpose memory and microprocessors chips that have the potential to be sold in the millions. The reduced production costs of Moses encourages researchers to experiment with very special-purpose VLSI designs or with other designs whose aim could not be justified by the cost of fabrication. For example, a researcher might design a chip solely for the purpose of exploring different ways of using silicon.

Moses is also effective as an infrastructure for helping students learn VLSI design. Because designs are submitted and approved electronically, turnaround time is limited. Limited turnaround ensures that students will receive feedback in the form of a realized object before they have forgotten what they were attempting to accomplish. Furthermore, limited turnaround together with lower production costs makes possible the development of a new design methodology and culture. Iterative design (successive approximation) and experimentation, rather than comprehensive top-down design, become feasible. Furthermore, because the system is based in part on the technology of the DARPA network, it provides a ready-made communications network among the new community of designers. Feedback from other participants in the form of comments or alternative design strategies make it more appealing to tinker with an existing design in the effort to improve it or to "outdo" a competitor. But this is just the beginning: the Moses experiment is currently being expanded through the development of *system kits*. These system kits enable designers to embed and test their chip designs in some overall system architecture. Students and researchers alike can now construct *a novel* system architecture in a matter of weeks rather than years.

It seems clear, then, that in addition to bringing new sorts of talents to bear on a difficult technical problem, providing hands-on learning experiences for a new generation of graduate students, and encouraging the growth of a new, experimental design methodology and culture, infrastructures such as Moses can help us explore the vast spaces of non-Von Neumann architectures. Given appropriate technologies, we could extend this model to apply to major scientific problems in a wide variety of domains. We need to continue these types of experiments in order to better understand both the technological issues and the "softer" issues of how to encourage the growth of productive social and communications infrastructures.

From hard to soft publications -- managing infrastructural change. As we have discussed, information technologies are bringing about major changes in both the conduct and communication of science. In order for these changes to benefit rather than harm the scientific community, we need to pay attention to the accompanying changes in social, economic, and communication infrastructures within the scientific community and to ensure that transitional structures are in place.

Consider the example of changes in scientific publications. Unquestionably, as electronic networks, laser printers, and high quality text-processing systems become widespread, the mechanisms for publishing scientific articles will be transformed. Current hardcopy scientific journals mailed to libraries and personal subscribers will give way to either softcopy renditions displayed on a workstation terminal or hardcopy versions printed on demand by laser printers. Although the end result of this transformation will be quicker, cheaper access to scientific research, the transition process could do permanent damage to the scientific community unless some care is taken to ensure the financial viability of the current publication infrastructures while new infrastructures and distribution mechanisms evolve.

For example, the photocopier has enabled researcher to make copies of articles appearing in scientific journals, thereby diminishing the value of having a personal subscription and potentially eroding the journal's financial base. Demand publishing will further in aggravate the problem, as will the concept of simply storing the article in publicly accessible databases without appropriate charge-back mechanisms. This is not to say that such developments are bad -- quite the contrary. However, if the financial basis for scientific publications is too eroded before new publication infrastructures are in place, we could suffer a serious scientific "brownout." Already publishers are investigating cost-reduction counter measures, such as the establishment of document protocols enabling scientists to submit their papers electronicly to journals in a form that can automatically typeset. But such cost-saving advances may not keep pace with the rapidity of technological development and the journals' decreasing revenue base, and the resulting drought may last longer than we expect. If so, special financial assistance for our current form of publication may be required.

A parable on managing infrastructural change. The foregoing example is meant to illustrate the importance of institutional and other infrastructures to the health of the scientific -- or indeed any social -- endeavor. During the 20th Century, the United States has repeatedly recognized the need to create nation-wide infrastructures in order to optimize technological advances and exploit their value for society as a whole. The creation of the interstate highway system and the development of the air-traffic control system exemplify both the need and effective policy responses to that need.

However, both the nature and the rapidity of advances in information science and technology complicate the problem of providing adequate infrastructures, perhaps beyond anything we have yet experienced. Rapid advancements in information technology could severely challenge the flexibility of extant mechanisms for establishing the infrastructures needed to realize the potential of technology. Reflect for a moment on how the infrastructures for the transportation of material goods would be the crucial limiting factor if automotive engineering had developed over the last decade as rapidly as has computing technology. A conservative analogy suggests that if cars had evolved as rapidly as computers during the past ten years, the average car would be capable of travelling well overa thousand miles an hour, achieve a fuel economy of at least 200 miles to the gallon, and cost approximately $500. Such advances would at least suggest fundamental changes in our interstate highways, to say nothing of driver training and school safety programs.

A Closing Example

Many of the points raised above have emerged from my own experience at Xerox PARC, a research center nationally renowned for generating many of the ideas that underly or enable the information age. One of the strategic research management principles that first impressed me when I arrived at PARC, was the emphasis on providing each researcher with state-of-the-art equipment. Indeed, the policy seemed implicitly to favor having a small number of wonderfully equipped researchers rather than a larger number of marginally capitalized reseachers. Furthermore the lab managers had never to consider the depreciation schedule of this equipment. They simply kept the equipment as long as there was nothing better that one could buy or build oneself. Only now, some seven years later, have I realized the productivity inherent in this implicit principle. I think it wise to generalize this policy to federal funding initiatives in support of scientific research. To retain our advantage in the development and use of information technology for science, it is important that we ensure not only that our universities and research centers are equipped today with state-of-the-art facilities but that this equipment can be replaced even if its lifecycle is far briefer than traditional depreciation schedules.

An equally important aspect of PARC research management is the recognition of the value of establishing information infrastructures in which each researcher has a personal workstation as well as unlimited access to high-quality print and file servers interconnected by high-bandwidth networks. Awareness of the power of an adequate infrastructure led one of our lab managers to supply out of his own budget a collection of network gateway processors to various Xerox line organizations. His move enabled the organizations to connect their local area networks into the networks around the company without having to individually justify the capital outlay. He thus initiated a global infrastructure where before had been only isolated local ones.

I have now lived with electronic message systems, demand publishing, powerful scientific workstations that facilitated rapid prototyping of complex software systems etc. for many years. Unquestionably the information age, at least for us, has brought about major changes in the way we communicate, interact, and even think. Invariably what we have found is that although nearly all our information-age adventures have a strong technological basis, we end up discovering again and again the need to better understand the human, organizational, and cultural components of the use of this technology. I firmly believe that by understanding these "softer" issues (often through cross-disciplinary eyeglasses), we can much more quickly realize the potential of information technologies and minimize the undesired wrenches they may invoke. I have also come to recognize how systems that a mere five years ago were the world's best can become fundamentally obsolete today, requiring extrodinary effort to make certain that we don't get trapped in one way of looking at or through the information age.

Epilogue

The following twist to a well-known poem by T.S. Eliot provides a timely reminder of the real purposes of technological innovation:

Where is the wisdom we have lost in the knowledge?
Where is the knowledge we have lost in the information?
Where is the information we have lost in the data?

Mr. **Walgren**. Thank you.

Those bells that were ringing were not aimed at you, but indicates there is a vote on the floor we should break for. We'll be back in about 10 to 15 minutes, so let's take a short recess. Thank you.

[Recess.]

DISCUSSION

Mr. **Fuqua** [presiding]. The task force can resume. I apologize for the interruption, but that is one of the problems around this place, we have to go and vote periodically.

Dr. Battin, you mentioned researchers spent about 90 percent of their time looking I guess and 10 percent researching. Is that—I was thinking about my brief time in college, that was about true then, I think, if you knew where to find the stuff, it was very easy. Is that something that is new? Has it gotten—or has the situation deteriorated in recent years? Is it a new thing that has happened?

Dr. **Battin**. I think it's probably a combination of all those, but in terms of what Dr. Newell was saying about the rate of range, we have seen an explosion of knowledge, as you know, in the last 20 or 30 years——

Mr. **Fuqua**. That was the part I was wondering. Has it more compounded itself in recent years?

Dr. **Battin**. Yes; and I think it compounded itself first with a print explosion and now with the explosion of information in machine-readable form and the creation of data bases all over the place with no infrastructure, as we have been talking about, of retrieval control or access. So that the invisible network is becoming almost—in the midst of all this sophisticated electronic communication capacity, we are finding we are depending again on the same old invisible network structures, which is not terribly productive, and there is just—generally in the sciences, it is true across the disciplines, but the literatures have exploded in ways, and the specialization has created a situation that if you remain in your very small specialty, you know the people working in that field, and you are in contact with them and so forth, but if you even so much as step one step out, you don't know where to go.

Mr. **Fuqua**. So it gets back to interdisciplinary probably more acute than in one specific, small, well-defined area of expertise.

Dr. **Battin**. I would think so. But even in those small areas, there is this split coming because of the ability to control access and the various societal forces, both in competition, and security, and so forth, that are causing a much greater limiting of knowledge about what information exists.

Mr. **Fuqua**. I know that this committee has under jurisdiction NASA, and I have been very much concerned over the years in the vast amount of information that has been sent back from satellites from scientific experimental probes; and for astrophysicists and others, there is not enough money or time to reduce all the reels of information that have been sent back. Some of it may be more useful than others, but it's been an extremely difficult thing to get all of it. They have taken certain parts but have a total analysis of all the information, some of it has been sitting around 10 or 15 years.

Dr. **Battin**. That is right, and it's been of great concern to the scientists in the universities, that they have not been able to gain any kind of access, and I think what is of greater concern now is that data is being turned over to private contractors who will find a way to sell it to us at a pretty high cost, so—that's going to change the nature of the kind of research that is done.

Mr. **Fuqua**. Dr. Newell.

Dr. **Newell**. I just wanted to comment on it. It seems to me one of our problems, and I think a number of other people, when you talk about networking, will be to find ways to communicate to you sort of how it can be different when fundamentally it is building up the infrastructure. There is an interesting example here. In our environment, for instance, there's electronic bulletin boards which people use, it's all part of this, and they are used in a way that helps to deal with exactly this problem.

People put up requests like, does anyone have a copy of that proceedings that I can't quite remember the name of? And they will put it up on the bulletin board, and some other student in the environment who knows about it will get it, and there is an ability I kept thinking of to make the invisible colleges visible. That really helps here. And this is a way in which the electronic networking, in fact, operates to provide styles that tend to help us, that doesn't deal with this public sector-private sector issue which Dr. Battin keeps bringing up, but relative to finding information in this information mountain that we have, I think that the electronic techniques, the planned solutions won't work, but the ones that emerge out of those networks will work.

Dr. **Battin**. Could I just reply to that? I happened to be out at Carnegie-Mellon about 1 year or so ago to discuss the development of some library-type infrastructure in the networks. We discussed bulletin boards, and one of your colleagues said, yes, he found out about Sadie Hawkins Day that way, he put up the note and said: "Does anybody know the origin of Sadie Hawkins Day?" Unfortunately, it took 3 weeks before all the erroneous information was sorted out from the correct information. I said: "Did you ever hear of your public library? You could have found that out in 1 hour."

There is some very good transfer. I think the main concern is the archival storage of that information so that it is there in a peer-reviewed way that you know the information you are getting is correct and so forth. For example, I spent 2 days at the National Library of Medicine on a planning committee for the future, and one of the very interesting facts that came up in the Union Carbide Bhopal tragedy recently, one of our major contributions to that was 4 inches of computer printout from Medlars, which represented the world literature on that chemical compound and what it was, because nobody knew it, and they didn't know how to treat the people or do anything about it because there was no information on what that compound was.

It is that kind of thing that is lost if you simply look at the information for what it can do for you at any particular point.

Dr. **Newell**. Let me agree with that absolutely and to try and make a virtue out of that, which is that no one technique here solves all these problems. The issue of validated data isn't solved at all by these bulletin board problems. It does, in fact, take different techniques. One of the things, it seems to me, the committee has to keep in mind is that when one hears there is a solution to a problem because it's described in global ways, it usually only solves a small fraction of that problem, and a different aspect, like the validation, isn't involved at all by it.

Mr. **Fuqua**. Dr. Brown.

Dr. **Brown**. I was going to make that comment about the validation. We're coming into an era where it's search, verify, and research as much as search and research. And one of the rules of the invisible networks we were talking about has to do with rumors passing around about the credibility of a particular data base, and I think, in fact, the worth of a data base is astronomically greater if you have some sense of the validity of that data in there, which is perhaps one of the reasons corporations are charging as much because that data is now verified in some ways.

Mr. **Fuqua**. This brings up another question that follows along with that. In the future, is there a single technology that could emerge that could handle this information?

Dr. **Newell**. Let's see; that is a hard question to answer in the following way: There is a single technology, and it is, in fact, digital technology, computers and the processing of it, and its feature is that it does, in fact, provide for this integration you were talking about. What you get in one form you can move to another. That technology, of course, is actually a buildup of hundreds of technologies. There are optical discs in it, and there are magnetic discs, and there are computers and networks, and they're all different technolgies, but they integrate together.

In that respect, yes, I think we will be moving. I was about to say slowly moving, but having talked about factors of 10 every 5 years, I guess I can't talk about that as slowly moving. We are moving to where there will be 15 or 20 years out in integrated technology, and it will, in fact, be called computer technology.

Mr. **Fuqua**. You think it will be 10 or 15 years?

Dr. **Newell**. No, I just think it will be a factor of 10 every 5 years, and I think that will go on for a while.

Let me again pick up the validation problem to use as a case example. One of the reasons why, as computer data bases and network access to them begin to arrive, we get all of these problems, we get problems about, are the documents on them unrefereed, and you don't know about them. There actually is an important interaction between these difficulties and two factors. One of the ones I already mentioned, which is every time you get a new capability, you don't use it right the first time, which is to say you don't assemble all the things necessary to make it right.

The second one is capacity, in which in some respects to associate with every number in a data base commentary about it requires sort of using ten times the amount of data storage. Now, when we first come into an era, there's more data storage than we have had, but there isn't that much more, you have to wait until you get further down the pike.

So the solution to many of our current problems will evolve over time as we learn and will require yet more capacity. So this business of when do we get an integrated technology is not at a given point in time. It continues to require more and more capacity as it grows over time to gradually take, say, the validation problem and find it possible that all files which are shipped back and forth also have associated notes and so forth. And so, the amount of bits that are required are, say, five times as much as it would otherwise, and you have to have things cheap enough so you can afford that before you can solve the validation problem.

That same story can be spun out with respect to every other aspect, about how imperfect it is when it starts, and usually a solution is learning how to do it, but requires more computational capacity, larger data bases, in order to do that.

Dr. BROWN. I think it is—I believe we are going to be moving into an era where technology can be brought to bear on technology, itself. We will begin to see systems that kind of run over data and find out buyers raise questions whether it should or not. I think we're going to be moving into situations where you have systems that try to do some checking on the validity of that data.

Mr. FUQUA. What would you think would be the appropriate role of the Federal Government in this, trying to bring this into one sensible technology, if that's possible?

Dr. NEWELL. I think the big role of government—and then let me come back to the Federal Government—of government is that government has a major responsibility for infrastructure, because infrastructure is almost defined by saying it is those things in our society which are of value to everybody, but no one person finds it sufficiently of value to him that he is prepared to put up the energy and effort to do it. It turns out, in the way our society has evolved, that the amount of general infrastructure in high technology areas that State and local governments can provide actually turns out to be very small. It need not have been that way, but that is the way we have evolved.

Consequently, the issue of supporting the infrastructure in this new technology is very strongly a Federal function. I think that's one of the key areas, and that's not to take anything away from the sort of local threats to access, which Dr. Battin has focused on a lot; they're independent issues, of course. In that issue of mediation between the open public research sector and the needs for private development and exploitation, that is in fact a—well, both Federal and State role to see how to lead the way between those two.

Mr. FUQUA. Dr. Battin.

Dr. BATTIN. Yes, I think that it is very important that information generated with taxpayers' money remain in the public domain, and that is not to say there is not a role for the private sector, because I think there is. I think this area is going to require enormous coordination of all kinds of formats of information, all kinds of generating agencies, and so forth, but I think it's important that we continue this tradition of federally-sponsored information to be available.

I just would like to make one point again——

Mr. FUQUA. I am concerned, what is the role—certainly we want it available that is created with taxpayers' funds, but what role is it in the Government to try and make sure this information is in a concise fashion that's available to all the researchers, and we don't have to spend the time that you so eloquently referred to or explained in trying to find all this data? We are wasting a lot of valuable time in doing that in person-hours.

Dr. **Battin**. Well, traditionally we have had this network of libraries in the universities and the Government. I hesitate to give any answers because I don't think there are any. We're dealing with such completely new problems. But it seems to me that we have to look at the organizations or the institutions in the society that can work in partnership with the Government in providing this kind of—first of all, the network, some kind of a network that is available, that provides what we call a convenience and invisible access from the work station to an international communication capacity, and then to make sure that we have also planned for the provision of information, the storage of it, and the access protocols so that citizens throughout the country can—and that has been done traditionally through the library structure.

We may wish to change that, but I think we have to look at how we have done it in the past and plan something that carries out that same function for the future.

Dr. **Newell**. Can I try one more on that?

Mr. **Fuqua**. Certainly.

Dr. **Newell**. One of the points I have been trying to make is that the power in this whole system, networks and so forth, is in the freedom, that is it is in the access and so forth, and there is a tension that is going on now in the current environment between whether one should really try to restrict things, restrict access, mostly because we are concerned with the exploitation of technology in the way of ideas.

The best defense against that—I mean, against having to restrict it—is in one sense to have a situation in which the gains from having the freedom of access are so apparent, that is what is making the engine run, and I would say you might consider that moving towards much better network capability in these kinds of things is going to make it clear for all of us that having freedom of access in getting the serendipity, having people contribute to it because they can contribute to all kinds of problems unless the open system really works, we can choose that one and won't have to move in the direction of restricting access, it seems to me, is an important issue.

And the Government role there is that it is sort of adjudicating that one. But on the positive side, its role is to believe that strong moves to support that information infrastructure will make it apparent that path of freedom is the right way to move.

Dr. **Battin**. I think there have been a lot of programs in the Federal Government to support reinstrumentation of scientific laboratories, to support the development of technology in private corporations through tax incentive measures, and so forth. It seems to me we have got to look at some of these mechanisms, applying those to the information technology, what we used to call libraries, information centers, however you want to define it today.

What I see in universities is libraries and computer centers coming together to form an infrastructure and somehow perhaps a temporary subsidy of those—or joint partnership—in order to make sure that our universities are really retooled in this whole information area. As I said, we have been doing it in other areas technology has hit, and I think it's the information area—and I think Dr. Brown mentioned this—the research in this area has been very poor. I would agree we need a whole new look at what information is, how it is used by people and the cost, and how we as a society fund those costs.

Dr. **Brown**. I think, though, we have to be—to go back to your point, Allen—a little bit careful. It's all too easy to say the Federal Government should step in and support all the costs of infrastructure——

Dr. **Battin**. I didn't say all the costs.

Dr. **Brown**. All right. But I think, in fact, we know very little about how to really enable powerful infrastructures—it's all too easy to pick up the analogies in the railroad system, the highway system, and so on, and so forth, and the library system. We are talking about radical new kinds of infrastructures here, although the networks are just the beginnings of the information we really infrastructurally care about. I think if, in fact, there were more understanding of the subtlety to install the infrastructures and the power forthcoming from creating infrastructures, it might be able to create push with pull where you find people more willing to bear the cost of that.

I think we ought to be sensitive to the fact we know so very little about how to really engineer cost-effective infrastructures. I think, for example, in one of the notes we got prior to this briefing, the Moses system is one of the most fascinating examples of the construction of infrastructure I have come across. Information off this would far transcend in power and scope what we are talking about here.

Mr. **Fuqua**. Mr. Volkmer.

Mr. **Volkmer**. No questions.

Mr. **Fuqua**. When we talk about networking all this information and free exchange that we generally agree is generally so important, how do you protect the individual property rights or copyrights or intellectual rights that people may have? Would that be an infringement or will it infringe on that?

Dr. **Newell**. Let's see, a general remark, and then a specific one. The general remark is that every time the power opens up, everything comes loose a little bit, and there's lots of opportunities and threats of such infringements because we have simply moved into a new world. This is not one that ever gets settled once and for all. The use of copyright—I am no expert on that at all—but the use of copyrighting files, and so forth, in which people put copyright in, seems to provide fairly good protection.

Mr. **Fuqua**. This unpublished information——

Dr. **Newell**. People put copyrights on unpublished information. Every time you create a document, you put it in. People have learned to do things now from the commercial sector in which you salt away and you program things that turn them off automatically so they self-destruct.

Consequently, if someone gets them and they get them in an authorized way after a week, they're not useful any more. So techniques arise—they take time to arise because in some sense until the threat becomes apparent, people don't invent those techniques. There is nothing inherent, there is nothing inherent in the technology that is going to make a permanent threat out of it, but I think the threats have to be dealt with as they come.

Ultimately—here, again, we come to a question of somehow resources, meaning that when we first get these systems, we only—we don't have enough extra resources to do the other things. The issue of using cryptographic techniques to encrypt everything, and to do that in a way that the users don't pay a big cost, the users are not aware in some sense there is a low encryption problem that is going on, but to do that in hardware so you get this automatic protection, that's something which systems can perform and will perform ultimately when the capacity to do it seems like it isn't such a big economic factor you can't do it.

A lot of facts about the use of electronic medium will go away when we find it possible to spend the resources and do that kind of encryption. That's one example of where there's nothing inherent in the technology, but there's always an immediate sense of problems that face this 5-year period that have to be settled down and worried about.

Let me give you another example of that. People worry a lot about somehow papers floating around in these networks being unrefereed. There is no reason for that to be the case any more than there are papers floating around unrefereed. The way you know something is refereed, you get it in a journal you know is refereed or you get it where there's a statement that says "Under penalty of perjury I claim this has been refereed," and that kind of statement can be associated with an electronic document as easily as with any other document.

The issue is social practice in which electronic documents floating around will acquire commentary. In fact, we are likely to end up with a system which the refereeing is infinitely better in electronic documents because a paper will carry commentary with it, and there will be a comment on this paper written by another scientist in which there is a three-paragraph evaluation, and that will go along with it. You don't have to read it if you don't want to, but it is there.

The ability to get something which is far better than our current refereed system is inherent in this technology, although again it takes both capacity in the system, and it take periods of social time to learn to come forward, and it doesn't happen right away. I fundamentally don't see any problem at all except to work ourselves through the details to somehow solve, for instance, that refereeing problem, which I know lots of people are very exercised about it, and I have never been able to understand quite why.

Dr. **Brown**. I think you are right, there is a social mechanism that has to be paid attention to, which often changes much slower. The refereeing is one kind of problem. Think about a whole notion of ownership of ideas and the willingness to put good ideas on community bulletin boards.

Dr. **Battin**. Well, I think the whole issue has become so complicated because in the past the copyright simply, it supported the free exchange of information, and if it were printed in a journal, and I brought the journal, I could show that to all kinds of people. Now, with the capacity in the electronic systems, you can sell the information, but you keep it so that you sell it—every time someone wants to use it, you sell it.

Mr. **Fuqua**. How about reproduction that sometimes copyrights prohibit, the transfer of that information?

Dr. **Battin**. For sale?

Mr. **Fuqua**. For sale.

Dr. **Battin**. But you could buy the copy in print, and then as many people as wanted to could come and look at it, this subsidized browsing. I think one of the things that has happened here, the research community, one of their ideas is to exchange as freely as possible. Now we have moved into a situation where there is a technique and a mechanism in order to make money on those ideas, and it has changed the way that—there are reasons people want to restrict access, and we haven't yet figured out how to deal with intellectual ownership concept in an electronic environment, and I think it's very different than the printed environment.

Mr. **Fuqua**. That had been violated, violated probably to the maximum, since the invention of the copy machine.

Dr. **Battin**. That is right. That changed the whole thing. Prior to that time, it hasn't worked. There is a further complication in the software area, which is fascinating to me, since we are all dealing with these enormous problems on software. What has happened here is because venture capital is generally fueling the development of software, therefore, the pricing mechanism follows those imperatives. In other words, you want big money, and you want it fast, and you want to get out before someone comes along with something that's going to put you out of business. Research communities are faced with buying products that are priced according to this kind of development or financing, and publishers have never had that kind of pricing mechanism before, and that is something entirely new for us. Who knows where that's going to go? It is a whole different economic mechanism there.

Dr. **Newell**. Let me emphasize, who knows where that is going to go? One of the problems, I guess these next statements are not meant to help you. One of the problems in the development of radically new things is the new social mechanisms that come forth. Thus, there has been a cultural strain—strain meaning a little path or stream, in the development of computers and networks about things ought to be really free.

One famous laboratory took the view that for about 10 years that it would have no pass words on its machine, that everyone from anywhere was to be free to come in and, in fact, it was a good thing if people came and looked over your shoulder while you were writing your manuscript, there is one very famous paper that was written by Marvin Minsky at MIT for which one of his proudest claims for this paper was, how many people had read this paper before he even got half way finished with it? And people he didn't know. He found out later they had come in.

That whole attitude which says we really are a totally open community and everything is free is somehow generated by the scientists involved as an appropriate response to living in this world, it is sort of diameterically opposed to the pressures that produce the kind of things Pat is talking about.

There is an interesting question of which is going to win out, how we are going to come to view this. And, again, I do believe there is a role of subsidization here, and I don't care at the moment whether it's subsidization by the Federal Government or industry supporting research in universities which creates these open communities, like the ARPANET is, which live long enough to establish the new and appropriate attitudes of how you ought to deal with it so people will feel like this is to be an open world.

Once they learn to feel that way and once we get the culture established that way, we'll raise our kids that way. That is the right attitude to have. It takes subsidy to get that started. I think there are some chancy issues about whether the commercial exploitation will produce a different set of attitudes which will force a whole technology in the wrong way. When I say it wasn't helpful, I am not smart enough to see how that one is going to go, all one can do is raise the red flag and believe the social mechanisms and time to work things out and, therefore, long-term investments in things are a very critical part of the problem—of the solution—the problem or solution, whichever way you want it.

Dr. BROWN. That actually has some bad consequences to it. It's curious now that we see the ability to pass documents around the network so easily, what does this do towards persons wanting to have subscriptions to professional journals? How is that eroding the financial bases for peer review in that scheme? It's going to be interesting to see how professional journals maintain a financial basis while this other kind of basis actually gets put in place.

Mr. FUQUA. Well, thank you, all three, very much for being here this morning and sharing with us your thoughts and questions you answered and questions you raised. We thank you all very much.

The task force will be adjourned.

[Whereupon, at 11:45 a.m., the task force was adjourned to reconvene on Tuesday, September 17, 1985.]

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